THE DEVELOPMENT OF A METHOD FOR THE DETERMINATION OF ACOUSTIC CHARACTERISTICS OF VENTILATING FANS

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by

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Submitted in Partial Fulfillment
of the Requirements for the
Degree of Naval Engineer
from the

Massachusetts Institute of Technology

1952

Authors

Department of Naval Architecture and Marine Engineering

May 16, 1952

ABSTRACT

Title:-

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The primary object of this series of tests was to develop a method by which the acoustic characteristics (frequency spectra and sound output) of axial-flow ventilating fans can be accurately and completely determined. In the process of this development, it was hoped that information could be obtained which would make it possible to calculate the sound power output of fans of known mechanical power and design characteristics.

Two fans of different capacities (500 and 1500 cfm) were tested at various speeds with and without moderate back pressure. The test setup consisted of a duct system of heavy construction into which the fan noise was directed. The duct

was terminated in an exponential horn to prevent acoustic reflections and standing waves in the measuring duct. Absolute sound-pressure level was measured in the duct using a miniature condenser microphone inserted therein and shielded by a windscreen. The output of the microphone was amplified and measured directly on a vacuum-tube voltmeter for overall levels. The noise spectra for the different conditions of speed and back pressure were obtained using a one-third octave-band filter set with band-center frequencies between 100 and 10,000 cps.

The data obtained for the smaller of the two fans indicated high sound-pressure levels in the frequency bands containing the fundamental and fourth harmonic of the blade frequency. As frequency increased, a general trend toward lower spectrum levels was observed. The same general trends were found to exist in the spectra of the larger fan; but, probably due to compressibility effects, the fundamental and harmonic peaks were not clearly observable. From the data for overall sound-pressure level, a formula was derived that gave power levels in close agreement with those measured for both fans above a speed of about 2600 RPM.

The consistency of data and conformity with theory were used as a basis for determining the adequacy of this new test method. The general agreement of trends

among all data taken, some agreement with axial-flow compressor theory, and satisfactory repeatability of data all indicated that the method is adequate to accomplish its proposed function. The satisfactory conformity of measured with computed overall power levels indicated that the empirical formula derived is of correct form.

Further work is essential in connection with the ventilating system source analysis. This work should include tests of axial-flow fans of other sizes and designs to substantiate or correct the findings of this investigation.

Thesis Supervisor:- Leo L. Beranek

Title:- Associate Professor
Electrical Engineering

Cambridge, Massachusetts
May 16, 1952

Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:-

In accordance with the requirements for the Degree of Naval Engineer, we submit a thesis entitled:- "The Development of a Method for the Determination of Acoustic Characteristics of Ventilating Fans".

Respectfully yours,

[illegible] E. Reynolds
Lieutenant (junior grade),

Kenneth E. Wilson, Jr.
Lieutenant (junior grade),
U. S. Navy

ACKNOWLEDGEMENTS

The authors wish to acknowledge their indebtedness to Professor Leo L. Beranek, Technical Director of the Acoustics Laboratory, Massachusetts Institute of Technology, for his continual help and criticism in the course of this investigation. We also thank Mr. Henry C. Lang for his advice in all phases of the work, Mr. George Kamperman for invaluable assistance in setting up the measuring system, and Miss Lydia Bonazzoli for the accomplishment of many little things throughout this study, and her typing of this final report. Finally, we thank everyone connected with the Acoustics Laboratory for his patience and help, without which the completion of this investigation would have been impossible.

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I. INTRODUCTION

Aboard ship, in office buildings, and in industrial plants, one of the important sources of noise is the ventilating system. If complete acoustic characteristics of these systems are determined, it is possible to make accurate predictions of noise levels in spaces supplied by these systems. Design engineers can then design the duct system mechanically and acoustically to attain a specified noise level in the ventilated spaces.

This study was the first step in a proposed acoustical analysis of ventilating systems. The ventilating system analysis will be divided into a study of fans, duct systems, and duct terminations. This investigation pertains to the first phase of the problem, the determination of the characteristics of axial-flow fans as acoustic power sources.

It was the specific purpose of this investigation to determine the adequacy of a proposed method for obtaining the acoustic characteristics of ventilating fans. The major consideration was the quality of the data obtained using the proposed test set-up. The quality of the data was judged by comparing the data obtained for the fans tested, under varying conditions of speed and back pressure.

The method presently used by the Navy of testing ventilating fans is felt to be somewhat limited in its scope and in the application of the data which can be obtained. This method, now in use at the Material Laboratory, New York Naval Shipyard, consists of sound measurements around the fan casing for varying conditions of back pressure and at constant speed. The measurements are made in an acoustically treated room (not an anechoic chamber), the acoustic qualities of which would be difficult or impossible to duplicate. No information is obtained on the frequency spectrum of the fan, and the noise transmitted down a duct cannot be determined. Therefore, these data cannot be used to assist in the prediction of noise levels in spaces supplied by a duct system. Its only value lies in making possible the intercomparison of various fans of the same type.

The proposed method for determining the sound-power output of a ventilating fan consisted, basically, of measuring the sound-power level in a duct connected to the fan exhaust. Reflections and standing waves are prevented in the measuring duct by terminating the duct in an exponential horn.

Various tests were made to determine the adequacy of the experimental duct system. It was found that sound-

pressure levels remained essentially constant as the microphone was moved axially in the duct, although the sound-pressure level was changed by radial movement of the microphone in the measuring duct. A windscreen was placed around the microphone in all tests to minimize the effect of wind noise on measured sound-pressure levels.

Two fans of different capacities were tested in this investigation. At various speeds and back pressures, frequency spectrum and overall sound-pressure levels were recorded. These data were studied to determine the appearance of high levels at the blade frequency fundamental and its harmonics. The overall levels for the two fans were compared, and an empirical formula was derived whereby overall power level could be predicted for a given fan operating at a certain speed.

The data obtained was consistent, and it was believed to be of a type which will be of value to the design engineer. Trends followed those expected in most cases, and the data compared favorably with results of tests for noise levels produced by airplane propellers. It is therefore felt that the proposed test method is a good one, and it warrants further investigation and exploitation.

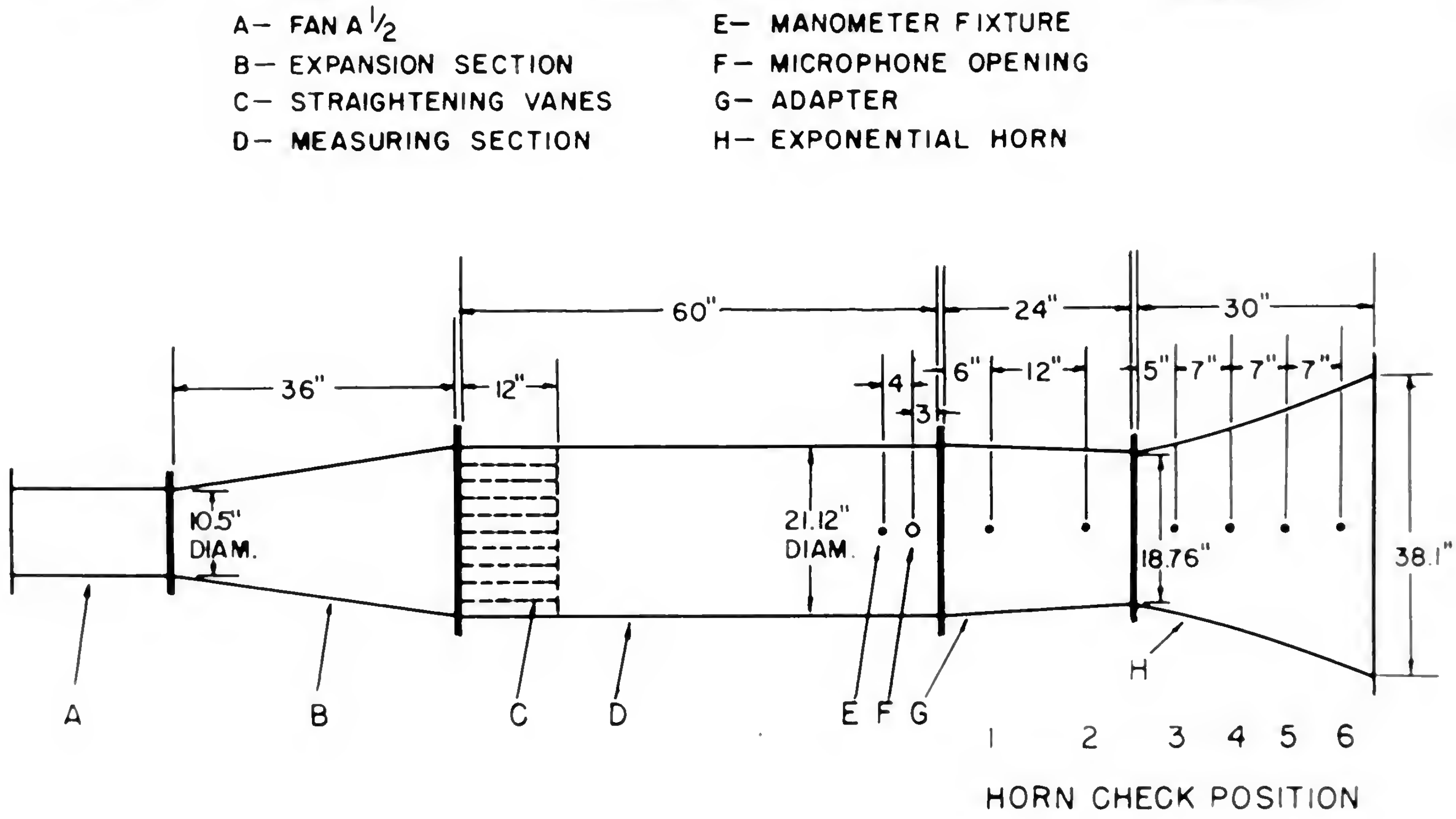
II. PROCEDURE

Since the purpose of this thesis is to determine an adequate and meaningful method of obtaining the sound-power output of ventilating fans, much time was spent in arriving at the method of testing the fans and in setting up the apparatus and equipment to be used in the fan tests. It thus seems fitting that the equipment and the test method employed should be described in detail.

A. Test Setup

1. Duct System (Fig. 1)

a. Measuring Duct - It was decided that sound-pressure level measurements should be made by placing a microphone in a duct which extended from the exhaust end of the fan. Measurements were to be made at a point about 8 feet from the fan. Since it was planned to test three fans, the A$\frac{1}{2}$, A1$\frac{1}{2}$, and A3, the duct was designed with the same inside diameter as that of the largest fan, that is, 21$\frac{1}{8}$ inches. This duct was 5 feet in length, of circular cross-section, and of $\frac{1}{16}$ -inch galvanized steel construction. In testing the two smaller fans, three-foot circular sections of



FAN AND DUCT SYSTEM

FIGURE I

increasing area were placed between the fans and the five-foot measuring duct. Nine straightening vanes were inserted in the duct about 4 feet from the fan in order to reduce the turbulence of air flow. A manometer connection and microphone opening were placed in the measuring duct as shown in Fig. 1.

b. Exponential Horn - In order to prevent wave reflections and resulting standing waves, an exponential horn was placed at the end of the measuring duct. This horn appeared acoustically to the fans and duct as an extending duct of infinite length.[1 *] It was decided that the horn could be constructed most conveniently with a square cross-section and using $\frac{1}{4}$-inch plywood. The square exponential section used in the horn made it necessary to insert a two-foot, steel circular-to-square cross-section adapter between the measuring duct and the horn. The adapter was designed with constant cross-section area.

c. Damping - In order to reduce induced vibrations in the duct, the outside of the entire system was coated with about $\frac{3}{16}$ inch of Komul, a standard Navy preservative, which has a tar-like consistency and color. It was readily observable that the application of the Komul damped the system considerably.

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2. Back Pressure

In order to create back pressure in the measuring ducts, a fine mesh screen, with four layers of cloth attached thereto, was secured firmly over the horn mouth. This arrangement was used during part of the tests, only.

3. Fans and Speed Control

Speed control was obtained in both fan tests by placing a variable resistance in the armature circuit of the direct-current motor supplied with the fan. A starting box was placed across the 110-volt d-c supply line.

4. Measuring System

The measurements in these tests included measurements of speed, power, back pressure, and sound-pressure level. The speed of the fans was measured by means of a stroboscope. The power input was measured only in the test of the A1$\frac{1}{2}$ fan, which has a series wound motor. The mechanical power was calculated from measurements of terminal voltage and motor current, using field and armature resistance determined from a blocked rotor test. Simpson meters were used for the electrical measurements. Back pressure was measured by means of a draft gauge manometer connected by a fitting in the top of the duct.

The sound measuring system was designed to obtain, as accurately and as simply as possible a measurement of the absolute sound-pressure level referred to 0.0002 dyne/cm^2. Overall as well as narrow-band measurements were desired.

Basically, the system consisted of an Altec-Lansing, Model 21-B condenser microphone; Altec-Lansing 40-db line amplifier; a Ballantine Laboratories, 0.001 - 100-volt vacuum-tube voltmeter; and a Telefon one-third octave filter. Each component was calibrated, and from this calibration direct readings of absolute sound-pressure level were determined.*

The 21-B microphone was chosen because of its small physical dimensions. Being small it was not expected to disturb seriously the sound field in the range of frequencies (100 - 10,000 cps) considered for the test. An effective windscreen with reasonably small dimensions could be fitted around it. Besides having a desirable size and shape, the frequency response was reasonably flat over most of the range considered.**

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PLATE I

FAN A$1\frac{1}{2}$ AND DUCT SYSTEM

SHOWING BACK PRESSURE SCREEN AND A$\frac{1}{2}$ EXPANSION SECTION

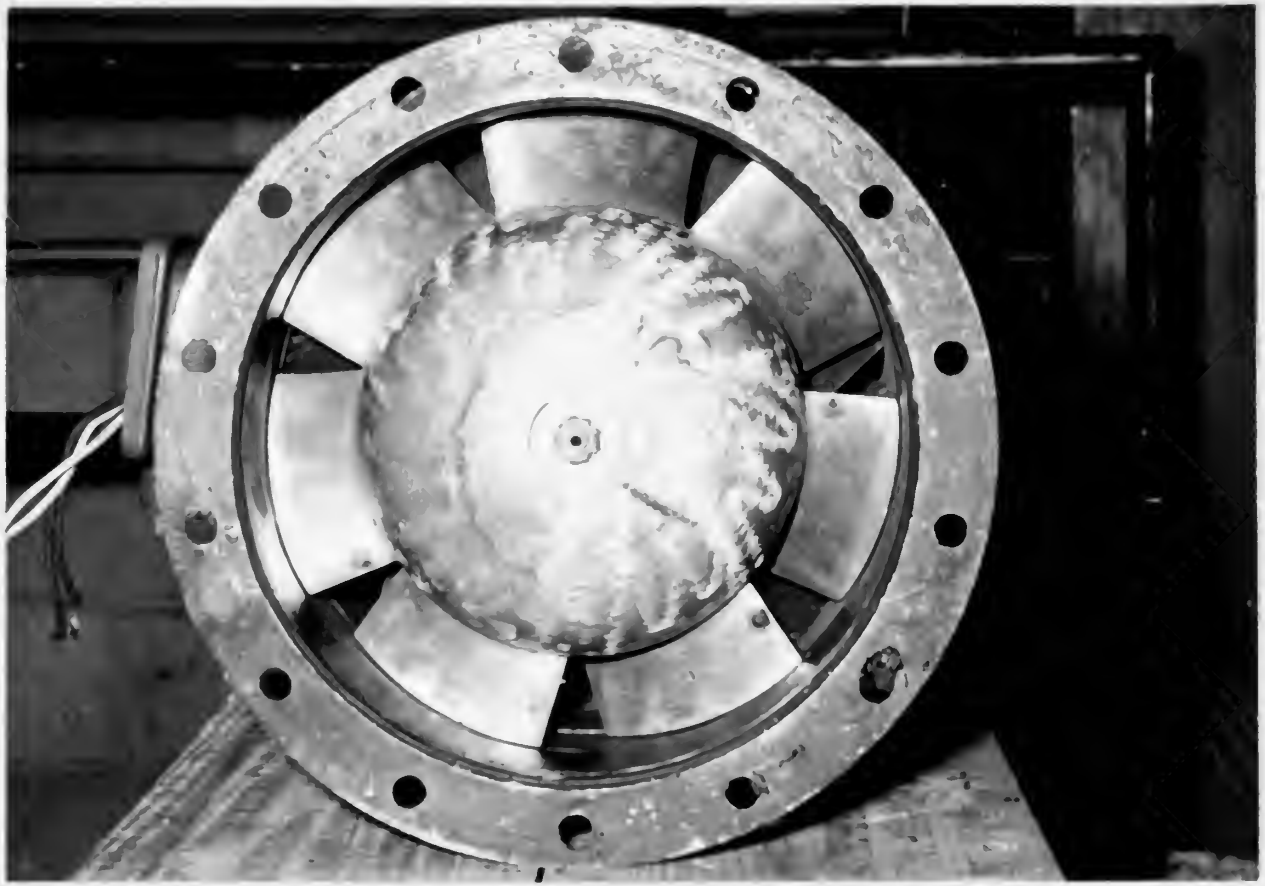

PLATE II

FAN A$\frac{1}{2}$ INTAKE END

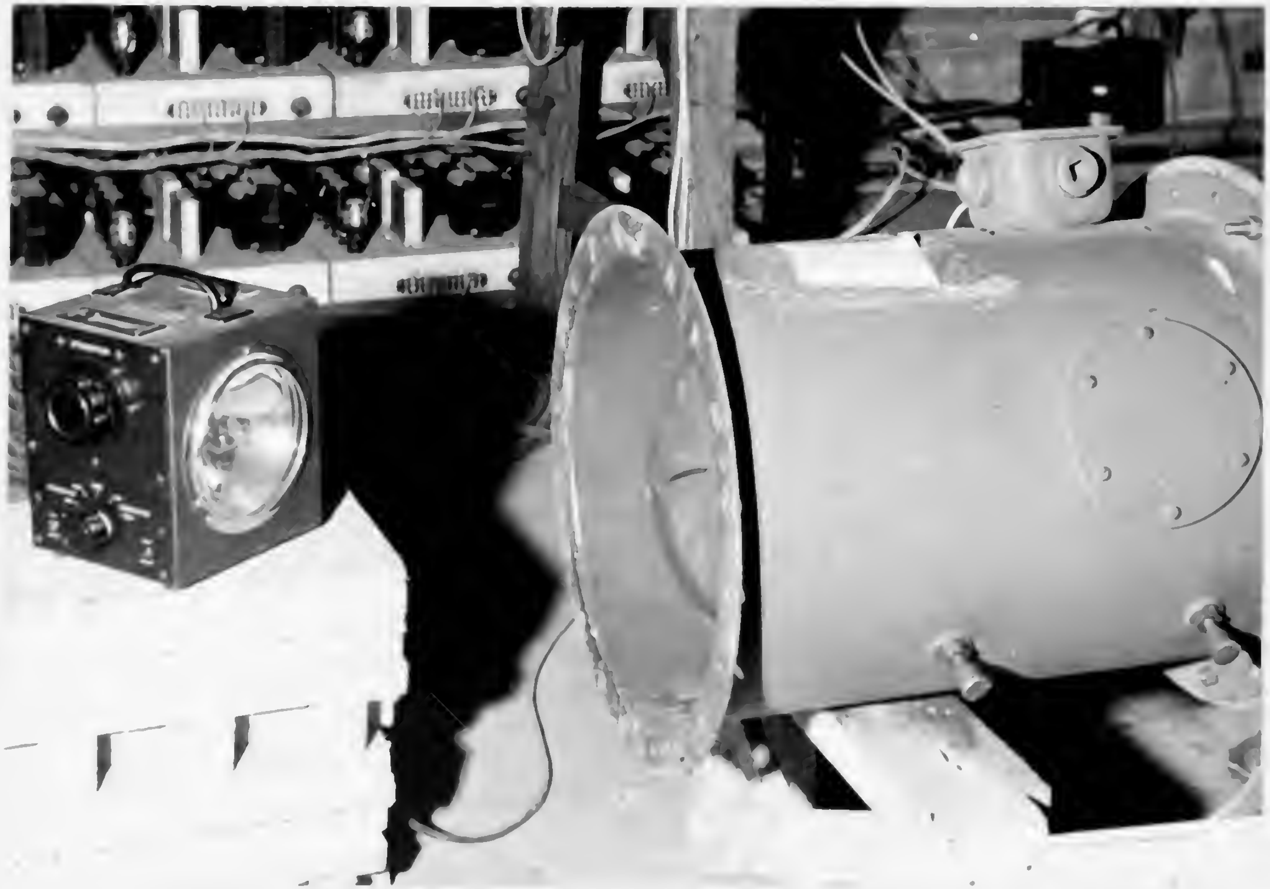

PLATE III

FAN A$1\frac{1}{2}$ AND STROBOSCOPE

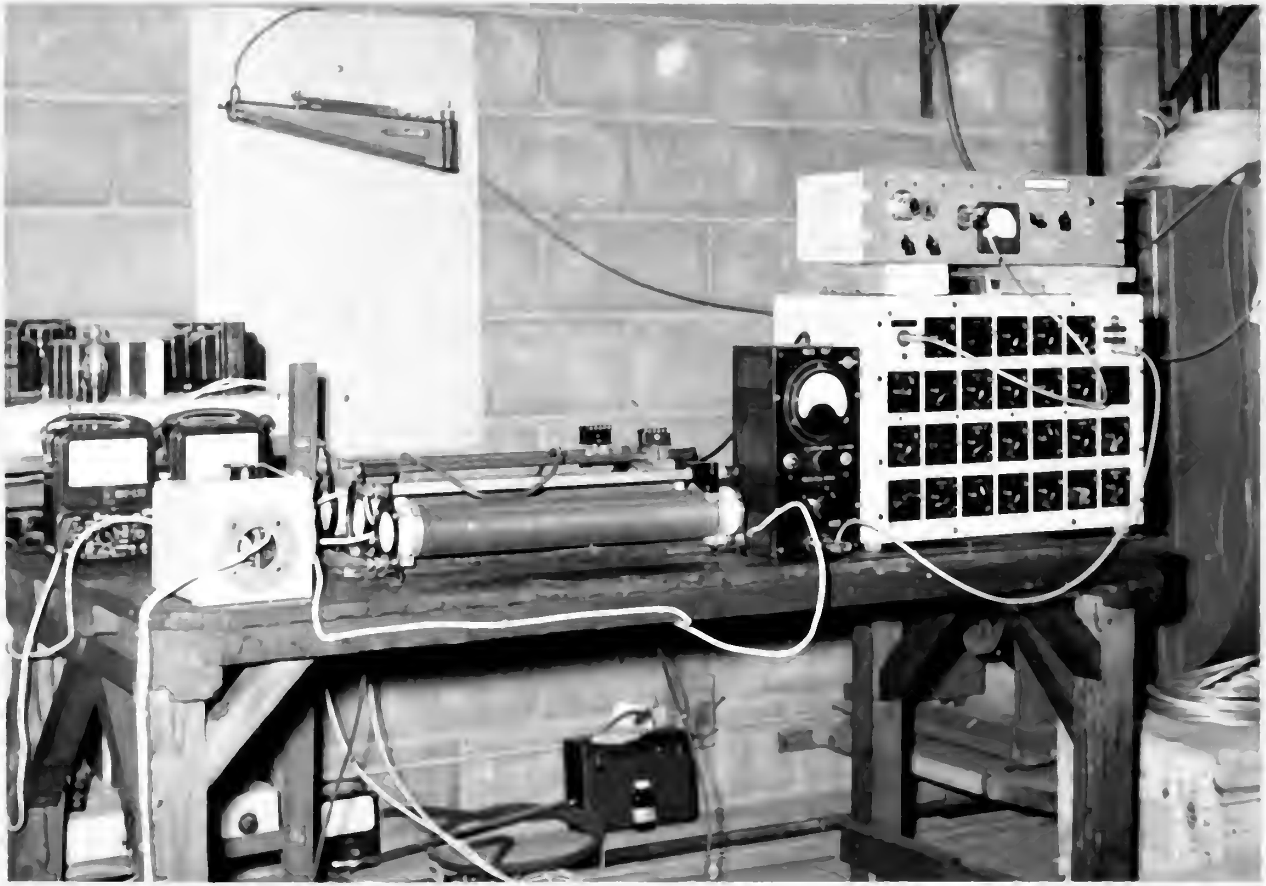

PLATE IV

FAN SPEED CONTROL AND
MEASURING INSTRUMENTS

PLATE V

INSIDE OF DUCT SHOWING MICROPHONE

MICROPHONE WINDSCREEN AND STRAIGHTENING VANES

The Altec-Lansing line amplifier was chosen for its stability as compared with the battery-powered amplifiers used in sound-level meters. Its response is relatively flat over the 100 - 10,000 cps band that was considered. This amplifier also contains the power supply for the vacuum-tube at the base of the Altec, 21-B microphone.

In order to determine the frequency spectra of the fans, the one-third octave filter was inserted between the amplifier and the voltmeter used for the SPL indication. The input impedance adjustment of the filter was set to 10,000 ohms to match the output of the line amplifier.

The filter was checked with an oscillator to ascertain the band shapes, the attenuation to be expected, and the bounding and center frequencies of each band.*

The Telefon filter has sharply defined pass bands and a flat response between 100 and 10,000 cps. The deviation is small and was neglected for the bands in which it applied.

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The "range of accuracy" of the measurements, mentioned above, was controlled primarily by the noise conditions around the Acoustics Laboratory. The accuracy of the equipment and calibration was better than the estimated accuracy of $\pm$ 1 db which resulted from reading fluctuations. There were large fluctuations in overall SPL and in spectrum measurements below about 1000 cps, but the measurements in the upper range of the spectrum were quite steady. Since the sound field conditions set a limit of precision of about $\pm$ 1 db, the small deviations from flat response in the filter and the microphone should not cause the limits in accuracy to be greater than $\pm$ 2 db.

B. Test Procedure

After the first fan, duct system, and measuring equipment were readied for the experiment, data were recorded to insure the adequacy of the horn in preventing standing waves in the measuring duct. Neglecting the horn-wall losses, the sound power passing through the duct is constant. The decrease in intensity level, as the microphone was moved out from the horn throat toward the mouth, could be predicted from theory to vary linearly with the axial distance from the horn throat.*

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This theoretical variation is plotted as the solid line in Fig. 10, page A-32. Sound-pressure levels were recorded at two axial positions in the adapter and four positions in the horn. Readings were also taken at off-center positions and were found to agree with values along the horn center line. The variation of levels at the various axial positions from the level at the horn throat were also plotted as a function of axial horn position for six fan-operating speeds. Due to fluctuations in the sound-pressure level readings, these values are considered accurate to $\pm$ 1.5 db.

It can be seen from Fig. 10, page A-32, that this $\pm$ 1.5 db region from the theoretical curve includes the majority (80 percent) of the measured points. It was felt that the experiment could be continued with the assurance that the exponential horn was adequately preventing standing waves.

Sound-pressure levels were observed in the measuring section and compared with those taken in the adapter. In this comparison, all readings were made with the microphone on the center line of the duct. At any particular speed, levels at the various axial positions

agreed to within 2 db. This was considered sufficiently close to the accuracy of any particular reading to justify the assumption that the axial position of the microphone in the duct did not affect the sound-pressure level measurement.

The next test was a determination of the effect of varying the radial position of the microphone in the duct-measuring section. For the $A\frac{1}{2}$ fan, readings were taken at 3, 6, and 8-inch distances from the duct center for 1000 and 2000 RPM. At the rated speed, levels were recorded at the duct center and at eight other radial positions, spaced 1 inch apart. The frequency spectrum check showed that, at rated speed, no variation in readings occurred below 500 cps and above 4000 cps as the microphone was moved radially outward from the duct center. However, between these frequencies, the sound-pressure level increased as the distance from the duct center was increased. The maximum difference between sound-pressure levels at the duct center and at position eight, 8 inches from the duct center, was 12 db - this difference being noted at about 800 cps. (Fig. 8 - page A-8). At 1000 and 2000 RPM, maximum difference was at a lower frequency. It is believed that these variations in levels were due to vibrations induced in the duct walls. No specific cause could be determined since a consistent

relationship linking the frequency of maximum sound level variation to the duct dimensions could not be found. It was therefore decided to make all frequency spectrum readings at the duct center.

Overall sound-pressure levels were taken at the duct center and at three radial positions off the center. An average overall sound-pressure level was then obtained from the average of the four measured sound pressures.

The final preliminary check was a determination of the contribution of wind noise to the SPL throughout the frequency spectrum. The test was made for the $A\frac{1}{2}$ fan at its rated speed. SPL's were measured with and without the microphone windscreen. The levels obtained with the screen were consistently below those measured without the screen, the larger differences occurring at high frequencies. (Fig. 9 - page A-10). This effect was expected, and it was decided to use the microphone windscreen for all further experimentation.

After these preliminary tests of the exponential horn, the effect of microphone radial and axial positions, and the effect of the windscreen, tests were commenced

to determine the sound-power output of the ventilating fan. SPL's were recorded for the $A\frac{1}{2}$ fan at 14 speeds ranging from 800 to 3450 RPM. For the $A1\frac{1}{2}$ fan, data were recorded at the same speeds as for the $A\frac{1}{2}$; and, in addition, readings were made at 3800, 4200, and 4600 RPM. Levels were recorded with no back pressure; and the runs were repeated with the back pressure windscreen in place at the horn mouth. SPL's were measured for both fans at each speed over a frequency range of 100 - 10,000 cps, using the one-third octave band analyzer for frequency selection. Overall levels were also recorded at each speed at four radial positions, and the average of these was taken as the overall SPL.

At the conclusion of these tests, the $A\frac{1}{2}$ fan was operated in the reversed position. Using the octave-band analyzer, SPL'S were measured in the duct with the fan running at rated speed.

III. POWER LEVEL

Power levels were used in the presentation of data obtained from these tests because in an acoustical analysis of ventilating duct systems, the basic quantity needed is acoustic power. Sound-pressure level in a duct, having no losses through its walls, decreases with increasing cross-sectional area; however, again neglecting losses, power level is independent of cross-sectional area.

Now consider a system in which wall losses are taken into account. If the sound power supplied to a duct system by a ventilating fan can be measured or computed, it is possible

1) To predict the sound-pressure levels in a room supplied by the ventilating system, if the duct wall losses and the propagation constants of the given system are known, and

2) To calculate the number of additional power absorption units in the duct system necessary to achieve sound-pressure levels below a specified value in the room.

Power level is defined by the following formula:-

$$PL = 10 \log_{10} \frac{\pi}{0.9 \times 10^{-13}}$$

π = Power in watts

The SPL in a duct neglecting transverse resonances is related to the power level by the following equation:-

$$SPL^{*} = PL - 10 \log_{10} A + 29.5 + \log_{10}\left(\sqrt{\frac{293}{T}} \times \frac{P}{760}\right) \text{ db}$$

A = Duct cross-sectional area in cm^2

T = Absolute temperature K^{o}

P = Pressure, millimeters of mercury.

In this investigation pressure and temperature conditions were sufficiently close to standard to be able to neglect the last term in the relationship above.

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IV. RESULTS

Frequency Spectra

The investigation of noise spectra of the fans tested produced apparently good results. The previously used test procedure for Navy ventilating fans did not include a spectrum check, so there was no direct method available for checking the quality of the data. Since the noise producing mechanism of the axial-flow fan is similar to that of an airplane propeller, it was felt that the noise resulting from the two sources should have similar characteristics. Reliable data are available concerning the behavior of an aircraft propeller as a function of speed and shaft power.[2-3] The airplane propeller data agreed generally with the spectra obtained above 100 cps from the ventilating fans.

The detailed investigation of spectra obtained from fan $A\frac{1}{2}$ at various speeds revealed distinct peaks at the fundamental and fourth harmonic of the blade frequency. (Fig. 2.) The vertical lines connect corresponding points on the spectrum curves and the harmonic curves. It can also be seen that the second harmonic had a negligible effect on the spectrum.

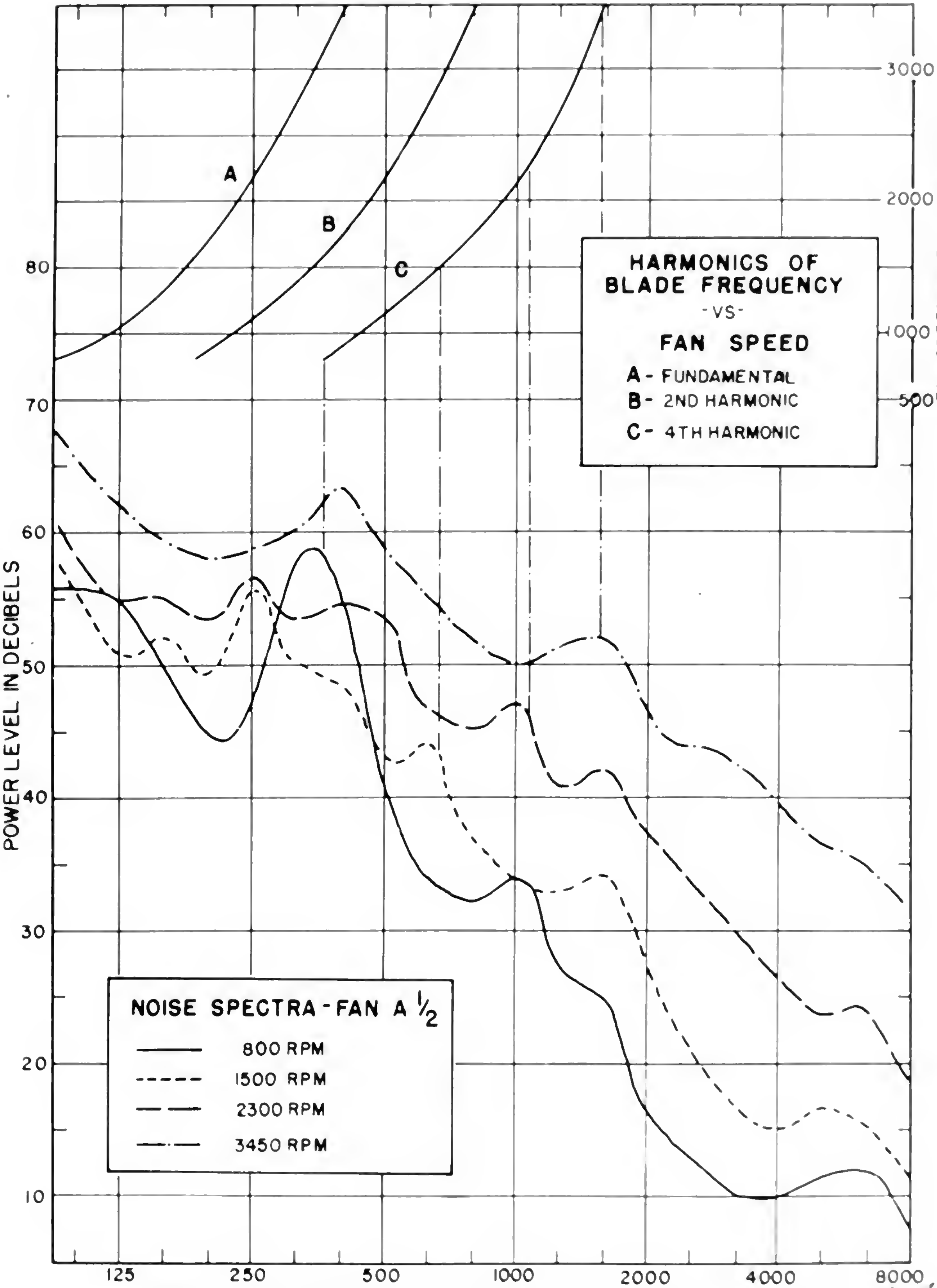

FIGURE 2

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5/9/52

This is not in strict agreement with a theory developed by Professor O. K. Mawardi[4] which has been applied to axial-flow compressors for pressure variation near the blades. This theory, based on the assumption of incompressible flow, predicts a wave form at the blade tip containing large second and fourth harmonic components. No attempt will be made to explain the absence of the second harmonic, but the following deviations from the conditions upon which the theory is based should be noted:-

a. Measurements were made relatively far from the blades.

b. The blade section is not the standard Joukousky air foil section used by Dr. Mawardi in his development of the theory for axial-flow compressors.

c. The flow is probably not perfectly incompressible as assumed.

The latter deviation probably has little effect in the case of the $A\frac{1}{2}$ fan, since a pressure check near the blades yielded a wave form which has predominant second and fourth harmonic components. On the other hand, compressibility and the high level of the turbulent noise are probably the reasons for the complete absence

of identifiable harmonic peaks in the spectra of the Al$\frac{1}{2}$ fan. (Fig. 3).

No analysis is known to the authors which applies to compressible flow around air foils. Therefore, the comparison with the propeller spectrum for agreement of trend is again used to estimate the quality of the test data. Although the octave spectrum of a propeller measured inside an airplane drops off much more rapidly than does that of a fan, as would be expected, the general trend is the same. This degree of agreement, coupled with the close agreement in trends for the two fans tested, indicates that the data presented probably give a true indication of the noise spectrum of the source.

Spectrum measurements were made for both fans with and without back pressure. The agreement in Fig. 4, indicated that the small increase in blade loading which resulted, produced an average reduction in spectrum level of about 2.5 db. It should be noted that the back pressures obtained were relatively small. For the A$\frac{1}{2}$, the maximum pressure obtained was 0.325 inches of water gauge, and for the Al$\frac{1}{2}$ the maximum pressure was 0.70 inches of water gauge.

[illegible] modifications [illegible] fans (Fig. 9).

[illegible] analysis is known [illegible] applied to compressor [illegible] airfoils. There-fore, the comparison with the propeller measurements [illegible] agreement of trend [illegible] only serve to estimate the [illegible] of the test data. Although the [illegible] spectrum of a propeller measured inside an airplane drops off much more rapidly [illegible] expected, the general trend is the same. [illegible] of agreement, coupled with [illegible] for the two fans tested [illegible] seemed [illegible] spectrum of the [illegible].

Spectrum measurements [illegible] with [illegible] in Fig. 9, [illegible] in reasonable blade loading which resulted [illegible] an average [illegible] in spectrum level [illegible] about 2.5 db. It should be noted that the back pressures [illegible] were relatively small. For the 4 [illegible] inches of water gauge [illegible] and for the [illegible] pressure was 0.7 [illegible].

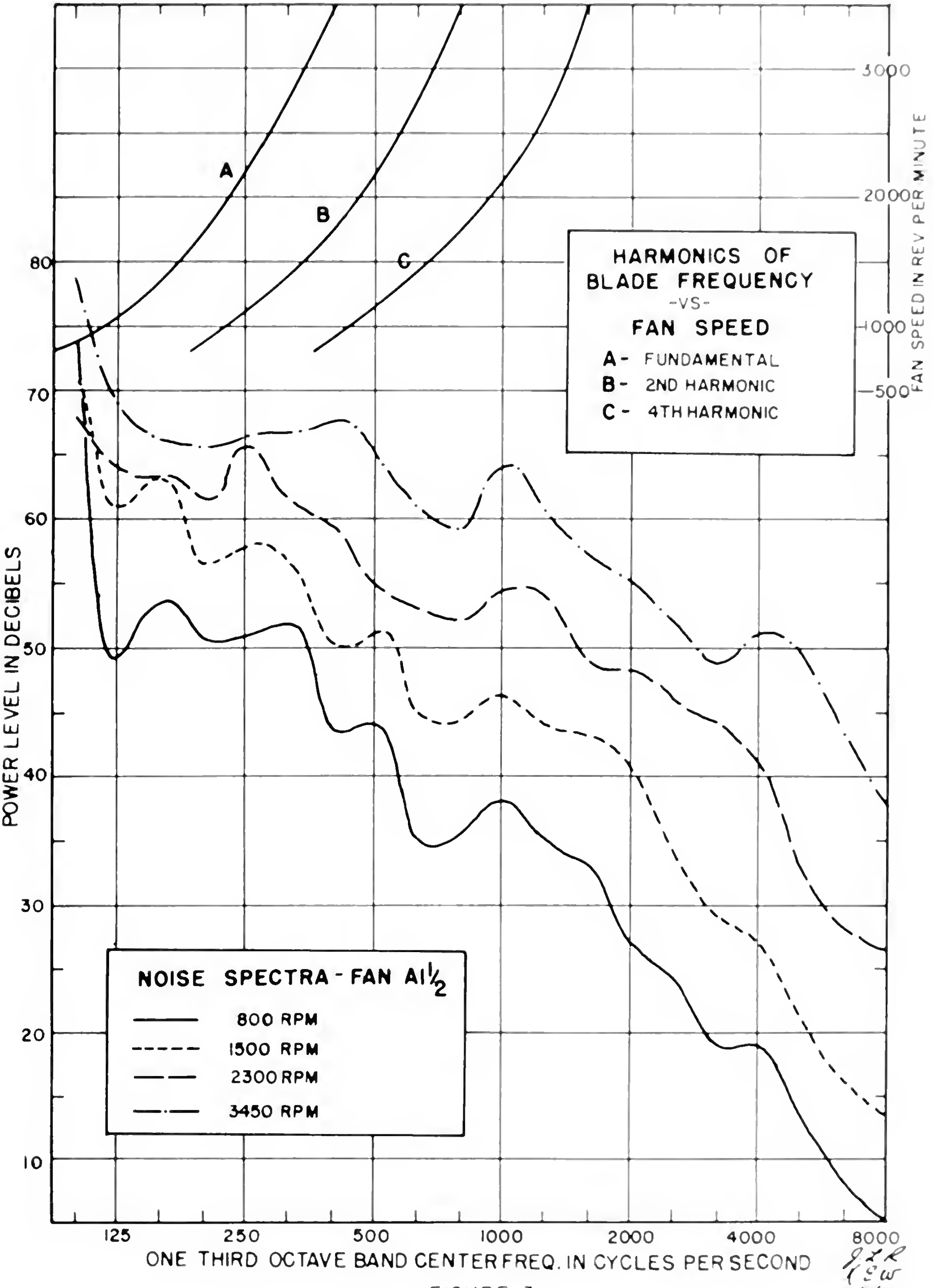

FIGURE 3

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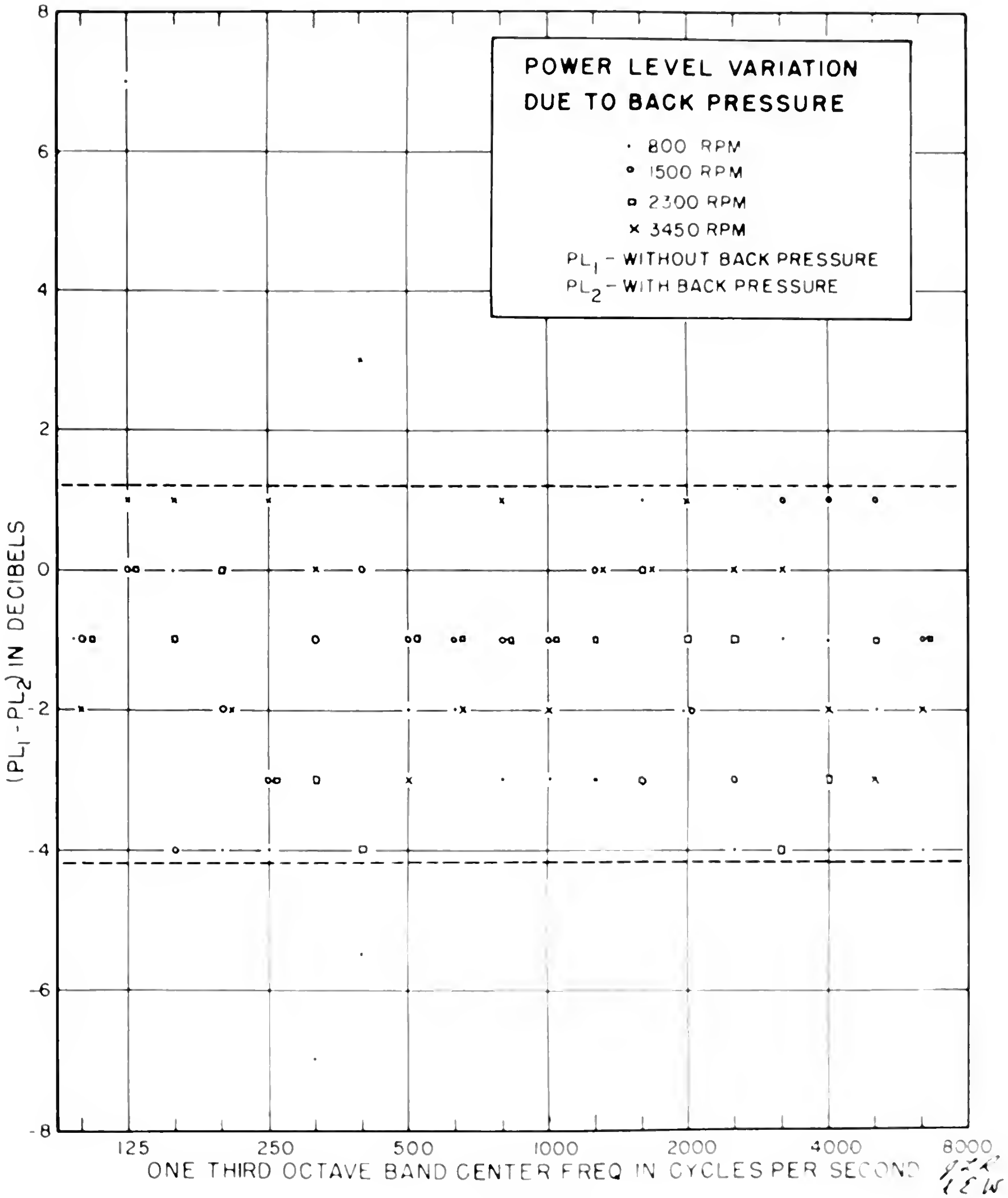

FIGURE 4

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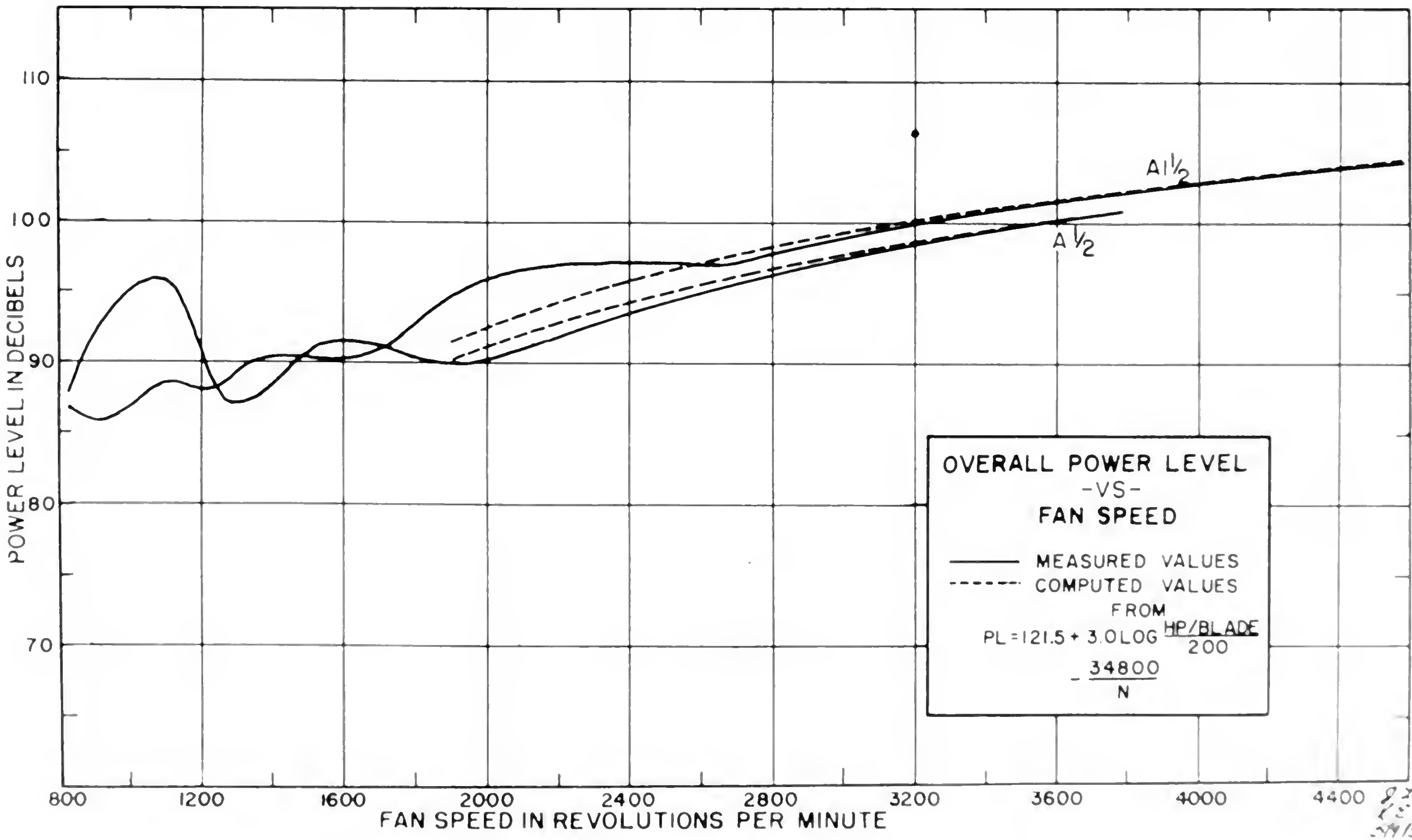
Overall Power Level

The average overall sound-power levels in decibels were calculated and plotted for the zero back pressure condition in Fig. 5. The small back pressures used caused very small reduction in overall power level from the zero back pressure case. At speeds above 2000 RPM, the plots give smooth curves of increasing power level with increasing speed. It is noted that the power level at 3200 RPM for the A$1\frac{1}{2}$ fan is 6.5 db higher than the smoothed curve. This value was caused primarily by an unusually high sound-pressure level in the 80 to 125-cps region. It is felt that this high level was a result of duct and associated system vibrations rather than the fan output. Large floor and duct vibrations were noted at this speed. Since overall power levels at all other speeds form a smooth curve, the value at 3200 RPM was neglected in drawing the smoothed curve.

The major cause of noise in the ventilating fans is the beating of the air by the fan blades and the disturbing influence of the fan straightening vanes and fan casing. In the A$\frac{1}{2}$ fan, high sound-pressure levels were noted at high frequencies after the fan had been operating for some length of time. It is



110
100
90
80
70
POWER LEVEL IN DECIBELS
800
1200
1600
2000
2400
2800
3200
3600
4000
4400
FAN SPEED IN REVOLUTIONS PER MINUTE
A 1½
A ½
OVERALL POWER LEVEL
-VS-
FAN SPEED
MEASURED VALUES
COMPUTED VALUES
FROM
PL = 121.5 + 3.0 LOG HP/BLADE / 200 − 34800 / N

FIGURE 5

believed that these high levels were caused by fan motor noise. This high frequency noise was clearly audible without earphones, and with earphones could be heard in frequency bands above 5000 cps. In testing the $A\frac{1}{2}$ fan, large differences were noted between the overall level at the duct center and the level near the duct wall.

It is believed that vibrations, caused by improper fan motor construction, were transmitted through the duct walls causing higher sound-pressure levels near the wall. In the $A1\frac{1}{2}$ fan, no motor noise was observed; and a maximum difference of 3 db was observed between levels at the duct center and near the wall.

An empirical formula has been derived for sound levels of airplane propeller noise.[2-3] This formula is based on data measured in the aircraft cabin and is a function of engine horsepower, propeller tip velocity, and the minimum propeller tip clearance. The sound-power levels computed by this formula correspond to that measured in the 75 - 150-cps octave.

A similar empirical formula has been derived by the authors for ventilating fans. In the aircraft measurements, the highest sound level was consistently in the 75 - 150-cps octave. In the $A\frac{1}{2}$ and $A1\frac{1}{2}$ ventilating fans, high levels were measured in this region; but at

some speeds, higher sound levels were observed at higher frequencies. Thus, it seemed more plausible to base the derived formula for ventilating fans on overall power level rather than the level of any particular octave. The formula below was derived to give sound-power levels in good agreement with the measured values. It was noted from the experimental data that the PL curves for the two fans were parallel above 2600 RPM. A tip speed term, as in the aircraft formula, would give different slopes for fans of different diameters. The desired result was attained by replacing the tip speed term with a function of rotational speed.

$$PL = 121.5 + 3.0 \log_{10} \frac{HP/Blade}{200} - \frac{34800}{n} + 10 \log_{10} \frac{N}{7}$$

Equation 1

PL = Power Level in Decibels

HP = Total Fan Horsepower

n = Fan Speed, RPM

N = Number of Blades

The total horsepower delivered to the A1$\frac{1}{2}$ fan by its series wound motor was computed at each speed by measuring the fan motor terminal voltage and the armature current. The armature resistance was determined by test to be 1.75 ohms. The horsepower, calculated from these measurements,* varied closely as the

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square of the fan speed over the speed range tested. (Fig. 11, page A-35) Motor rotational losses were neglected in computing the horsepower developed at each speed. In the $A\frac{1}{2}$ unit, the horsepower delivered by the compound wound motor to its fan was not measured. The measured horsepower for the $A1\frac{1}{2}$ fan at rated speed (3450 RPM) was 0.382 HP with no back pressure applied. The motor name plate for the $A1\frac{1}{2}$ fan indicated a rating of 1.1 HP at rated speed. For the $A\frac{1}{2}$ fan, the rated horsepower at 3450 RPM was 0.4 HP. It was assumed that the measured horsepower for the $A\frac{1}{2}$ fan at 3450 RPM with zero back pressure was

$$\frac{0.4}{1.1} \times 0.382 = 0.140 \text{ HP}$$

The horsepower at the other speeds were then calculated by assuming that in the $A\frac{1}{2}$, as in the $A1\frac{1}{2}$, total fan horsepower varied as the square of the speed. These horsepowers were then used in Equation 1 to obtain computed sound-power levels.

Equation 1 is plotted for both fans in Fig. 5. The derived sound power formula gives agreement to within 1 db of the measured values in the speed range above 2600 RPM for both fans.

The variation in octave-band spectrum caused by reversing the fan position, making the measuring duct end the intake end, is shown in the frequency spectrum plot of Fig. 6.

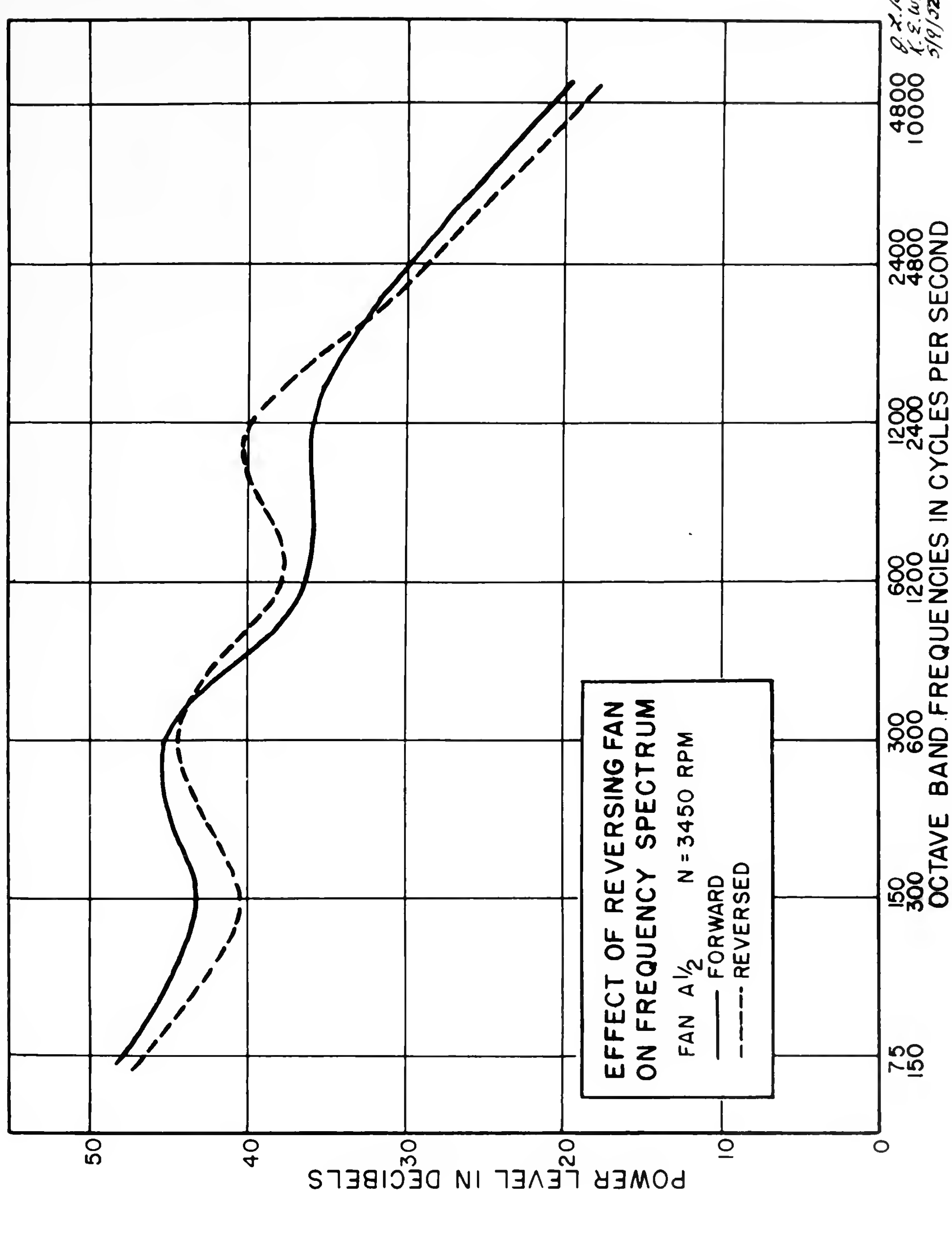
EFFECT OF REVERSING FAN
ON FREQUENCY SPECTRUM
FAN A 1/2 N = 3450 RPM
FORWARD
REVERSED
POWER LEVEL IN DECIBELS
0
10
20
30
40
50
75 150
150 300
300 600
600 1200
1200 2400
2400 4800
4800 10000
OCTAVE BAND FREQUENCIES IN CYCLES PER SECOND

FIGURE 6

V. CONCLUSIONS

The points on which a proposed test method should be judged are:-

A. Quality of data obtained

B. Usability of data

C. Repeatability

D. Characteristics of the test equipment

   1. Test Setup

      a. Reproduceability

      b. Cost and ease of manufacture

   2. Measuring System

      a. Accuracy

      b. Availability

      c. Time required to obtain accurate measurements

In the development of a new test procedure, probably the most difficult point to judge accurately is the quality of the data obtained. On the basis of the consistent trends in spectrum measurements and smooth variations in overall PL as a function of fan speed, the data appear to be satisfactory. This appearance is further reinforced by the good repeatability of datum points which was observed. Variations from one

time of measurement to another seldom exceeded 1 db. A further indication that the data obtained are good is the partial agreement of the spectra of the $A\frac{1}{2}$ fan with theory applied to axial-flow compressors.

Usability of the data is another point which is difficult to determine when the type data obtained has not been available before.

It is known that this type of data will permit accurate calculations of sound-pressure levels in rooms supplied by a ventilation system if, in addition, the power losses in the duct are known and if available propagation constants in duct liners are used. In other words, only if power levels are known can predictions of levels in rooms be attempted. In addition, this type of measurement permits intercomparison of fans on a logical basis. Also, the spectra obtained could possibly be employed by design engineers to determine the exact origin of the fan noise and thereby assist in redesign to reduce the sound output of axial-flow fans. Through empirical formulas, such as the one presented here, more exacting acceptance standards might be set down. Consideration of only these possibilities leads to the conclusion that this test method yields usable data.

It the test method qualifies on points A, B, and C, (p. 29) it is then worthwhile to examine the test setup. In the arrangement used for these tests, it can be seen that the duct and exponential horn, built of standard size materials from simple plans lend themselves to exact reproduction. This fact is important in standardizing an acceptance test procedure. Another point in favor of the system is that it is inexpensive and easy to manufacture.

The final component to be considered in a test method is the measuring system. Again, the results of an examination are favorable for the system employed. Each component is of good accuracy when properly calibrated. None are dependent upon battery power and are therefore quite stable. Furthermore, the necessary calibration is quite simple and requires little time. Finally, the time required to obtain good data is short due to the relatively small swing in the readings afforded by the use of the one-third octave filters as opposed to a sound analyzer. Because one-third octave band filters are not readily available in the United States, full octave-band filters should probably be specified for use in government test facilities.

The indications are that on all points considered, the proposed method fulfills the requirements. Although the evidence is not conclusive concerning the quality of the data, it is felt that further exploitation of this procedure is warranted because of the simplicity of the setup and the varied types of data obtainable.

VI. RECOMMENDATIONS

In the light of the results obtained and the conclusions reached, the following recommendations are suggested relative to further study of the ventilating fan test proposed herein:-

1. The duct system and measuring equipment used in this test, or a similar test setup, should be employed for future investigation.

2. Several other fans should be tested to confirm the accuracy of the overall sound-power formula and to compare the frequency spectrum with those obtained for the A$\frac{1}{2}$ and the A1$\frac{1}{2}$ fans. The overall sound-power level formula, as stated in the report (or one derived to give good agreement with measured data for these and other fans), could be used as a design criterion or as an acceptance specification for standard Navy and for commercial ventilating fans.

3. Test A$\frac{1}{2}$ and A1$\frac{1}{2}$ fans with a-c drive motors to investigate the effect of motor noise.

4. Higher back pressures in the duct should be arranged for without disturbing the sound field. Investigation of power levels at these increased fan loadings should be made.

5. Investigate more fully the effect on sound-pressure level of varying the radial position of the microphone. Check this effect at various speeds and frequencies in order to obtain a relation between radial sound-pressure level variation and fan speed, frequency, and duct dimensions. (The radial change in levels for the $A\frac{1}{2}$ fan may have been caused by poor motor construction.) Further damping of the duct, using sand, may decrease this effect.

6. Increase measuring duct length and increase the number of duct straightening vanes to reduce possible turbulent effects at the measuring section.

7. Make sound-pressure level measurements at the intake end of the fans and obtain complete directivity data for this end of the fans.

8. In order to obtain frequency data quickly with an adequate degree of frequency selection, at least a one-third octave filter should be used. For a more accurate investigation of the appearance of the fundamental blade frequency and its harmonics in the fan sound output, a frequency analyzer or wave analyzer with a very narrow band should be used.

9. The test set-up should be mounted on a rigid foundation (cement floor) to aid in minimizing system vibrations.

10. To eliminate motor noises being transmitted through the duct walls to the measuring section, insert a short (about 2") canvas sleeve between the expansion section and the measuring duct.

11. Test this and other kinds of microphone windscreens to determine more precisely their effect on the frequency spectra and overall power levels. The windscreen used in this series of tests is shown in PLATE V.

APPENDIX

Contents

A. APPARATUS

1. Octave-Band Analyzer, General Radio Company Type 1550-A, No. 101.

2. Slide-wire Rheostate (3)

   (1) 107 Ohm, 3.3 Amps. No. 96737

   (2) 120 Ohm, 2.5 Amps, No. 3383X, 1748X

3. MIT Acoustics Laboratory Condenser Microphone Amplifier AL-167

4. Ballantine Laboratories Voltmeter Model 643, No. 196266.

5. One-Third Octave Band Analyzer, Telefon Fabrik Automatic A/S and Kobenhaven Filter 11203-4.

6. Strobotac, Type No. 631-B, No. 11071, General Radio Company.

7. Motor Control Starting Box, Cutler-Hammer Company.

8. Microphone, Condenser, Type 21-B, Altec-Lansing Corporation

9. Simpson Voltmeters (2) Simpson Electric Company Chicago, Model 260, Nos. 837130, 837131.

10. Elison Inclined Draft Gage, Elison Company Chicago.

11. U. S. Navy Axial-Flow Fan, A$\frac{1}{2}$ DIW5, Mfr. Ser. No. A-8704. Buffalo Forge Company, Buffalo.

12. U. S. Navy Axial-Flow Fan, A1$\frac{1}{2}$ DIW5, Mfr. Ser. No. A-22201. Buffalo Forge Company, Buffalo.

B. DATA

1. Calibration Data

a. System

$1 \text{ volt} = 1 \text{ dyne/cm}^2$ $\qquad V_{out}$ = Amplifier Output Voltage

V_{mic} = Microphone Output Voltage

Response of 21-B microphone to -48.6 db is about -45.5 db

$$20 \log_{10} \frac{V_{mic}}{1} = -45.5 \text{ db for } 74 \text{ db}$$

$$\log_{10} V_{mic} = \bar{2}.275$$

$$V_{mic} = \frac{1}{188} = 0.0053 \text{ v for } 74 \text{ db}$$

Line Amplifier Gain = 40 db

$$20 \log_{10} \frac{V_{out}}{V_{mic}} = 40 \text{ db}, \quad \frac{V_{out}}{V_{mic}} = 100$$

$$V_{out}\ (74 \text{ db}) = 0.53 \text{ v}$$

$$V_{out}\ (80 \text{ db}) = 1.06 \text{ v} \approx 1.0 \text{ v}$$

This gives scale factor for Ballantine Voltmeter

b. Microphone Calibration (See Fig. 7 for frequency calibration of microphone.)

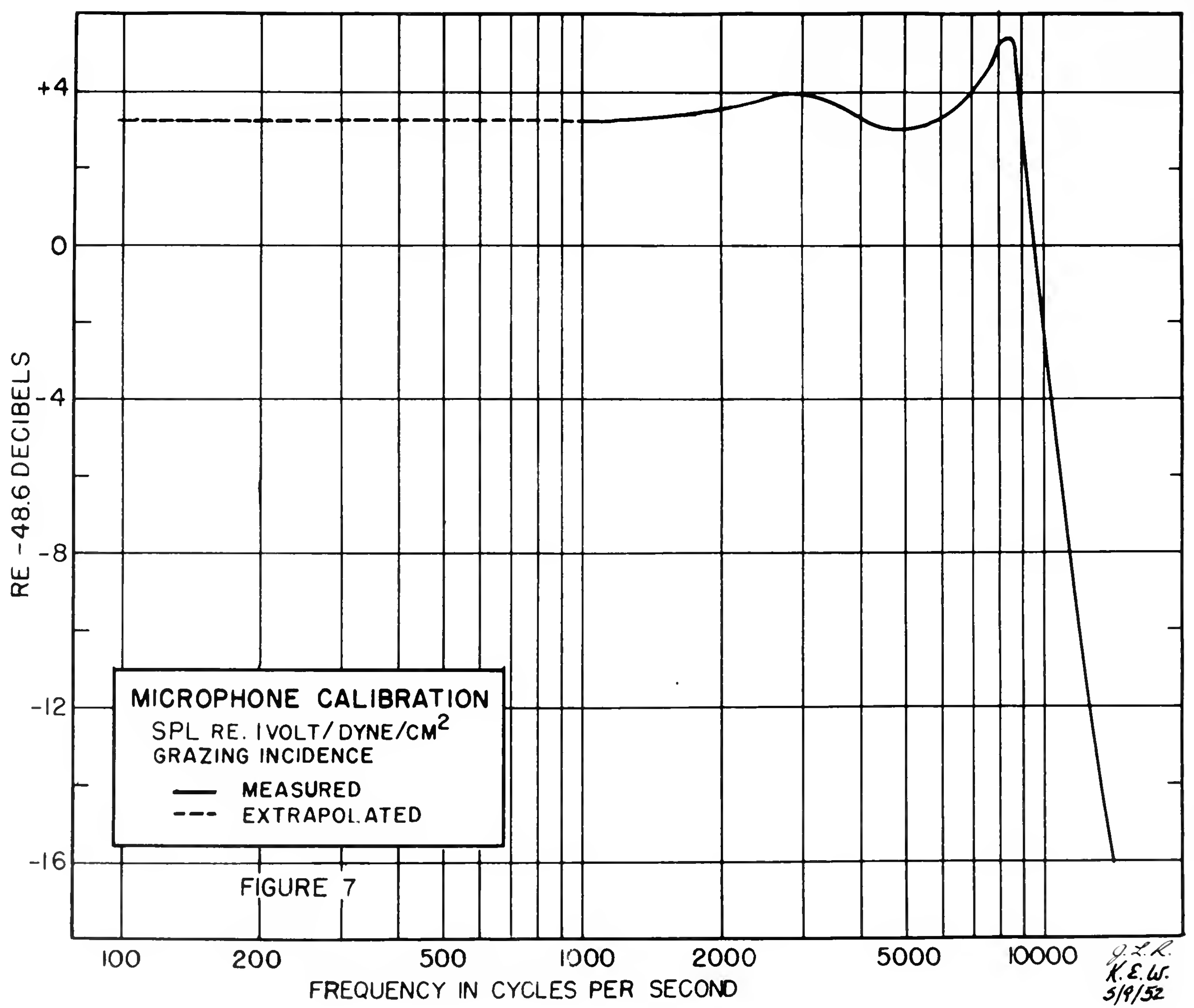
MICROPHONE CALIBRATION
SPL RE. 1 VOLT/DYNE/CM²
GRAZING INCIDENCE
MEASURED
EXTRAPOLATED
+4
0
-4
-8
-12
-16
RE -48.6 DECIBELS
100
200
500
1000
2000
5000
10000
FREQUENCY IN CYCLES PER SECOND
J.L.R.
K.E.W.
5/9/52

FIGURE 7

c. One-Third Octave Filter Calibration

Band Number	Band Center Frequency	Band Bounding Frequencies	Band Level Correction
1	50	45-57	-4
2	63	57-71	-3
3	80	71-90	-2
4	100	90-114	-2
5	125	114-142	-1
6	160	142-180	-1
7	200	180-228	-1
8	250	228-284	-1
9	320	284-360	-1
10	400	360-456	0
11	500	456-568	0
12	630	568-720	0
13	800	720-912	0
14	1000	912-1136	0
15	1250	1136-1440	0
16	1600	1440-1824	0
17	2000	1824-2272	0
18	2500	2272-2880	0
19	3200	2880-3648	0
20	4000	3648-4544	0
21	5000	4544-5760	-1
22	6300	5760-7296	-1
23	8000	7296-9088	-2
24	10000	9088-11520	-2

2. Horn Check

Readings of SPL* at axial positions along horn length, using fan $A\frac{1}{2}$.

Axial Horn Position	Ambient	Speed 1000	1500	2000	2500	3000	3450
1	48	65	60	62	64	68	69
2	48	65	59	60	64	67	69
3	48	63	57	59	63	66	67.5
4	48	61	57	57	63	62.5	66
5	48	60	57	56.5	61	62	66
6	48	58	57	56	60	60.5	63

*All readings ± 1.5 db

ΔIL = ΔSPL (Reference Sound-Pressure Level at Horn Throat, Position 2)

ΔSPL Position	Speed 1000	1500	2000	2500	3000	3450
3	-2	-2	-1	-1	-1	-1.5
4	-4	-2	-3	-1	-4.5	-3
5	-5	-2	-3.5	-3	-5	-3
6	-7	-2	-4	-4	-6.5	-6

See Fig. 10, p. A-32

3. Radial Check (A$\frac{+}{2}$)

SPL

		n - 1000				n = 2000				n = 3450								
f	Band	0"	3"	6"	8"	0"	3"	6"	8"	0"	1"	2"	3"	4"	5"	6"	7"	8"
100	4	66	66	65	65	75	73	72	72	78	77	78	78	78	78	78	78	78
125	5	63	63	63	63	71	69	68	69	77	76	77	76	77	77	76	76	77
160	6	69	69	69	69	68	69	69	68	75	75	75	76	75	76	76	75	75
200	7	64	65	64	64	68	70	69	69	74	75	74	74	74	74	74	75	75
250	8	63	64	65	66	76	77	76	75	77	76	76	77	76	78	73	78	77
320	9	63	67	73	74	75	75	75	74	78	78	78	79	78	79	79	79	79
400	10	77	84	88	90	72	73	74	74	83	83	82	82	83	84	84	84	84
500	11	71	86	91	94	69	91	73	76	79	80	80	80	81	81	82	82	83
630	12	54	64	70	73	66	67	69	69	78	78	78	78	79	79	79	80	80
800	13	58	57	61	63	74	74	73	76	75	76	79	80	82	84	85	84	87
1000	14	52	54	57	60	71	70	69	74	73	74	76	77	79	80	81	81	82
1250	15	49	56	55	57	64	65	66	68	76	76	77	78	79	80	80	80	81
1600	16	50	51	52	52	65	65	66	67	78	76	77	79	81	81	81	79	80
2000	17	40	43	44	46	60	62	64	67	73	74	74	74	73	74	76	77	79
2500	18	39	41	40	42	58	59	59	61	72	73	73	72	72	73	74	74	75
3200	19	39	38	38	37	54	53	54	55	72	71	71	71	71	71	71	72	72
4000	20	40	39	41	40	51	52	52	52	70	70	71	70	70	70	71	70	70
5000	21	40	39	40	39	51	51	52	52	66	66	67	67	67	67	67	67	67
6300	22	41	41	40	40	52	51	52	53	66	66	66	66	65	65	65	65	65
8000	23	37	37	37	36	49	48	50	49	63	63	62	62	63	62	62	62	62
10000	24	31	31	32	31	46	47	49	47	60	59	58	58	60	59	59	59	58

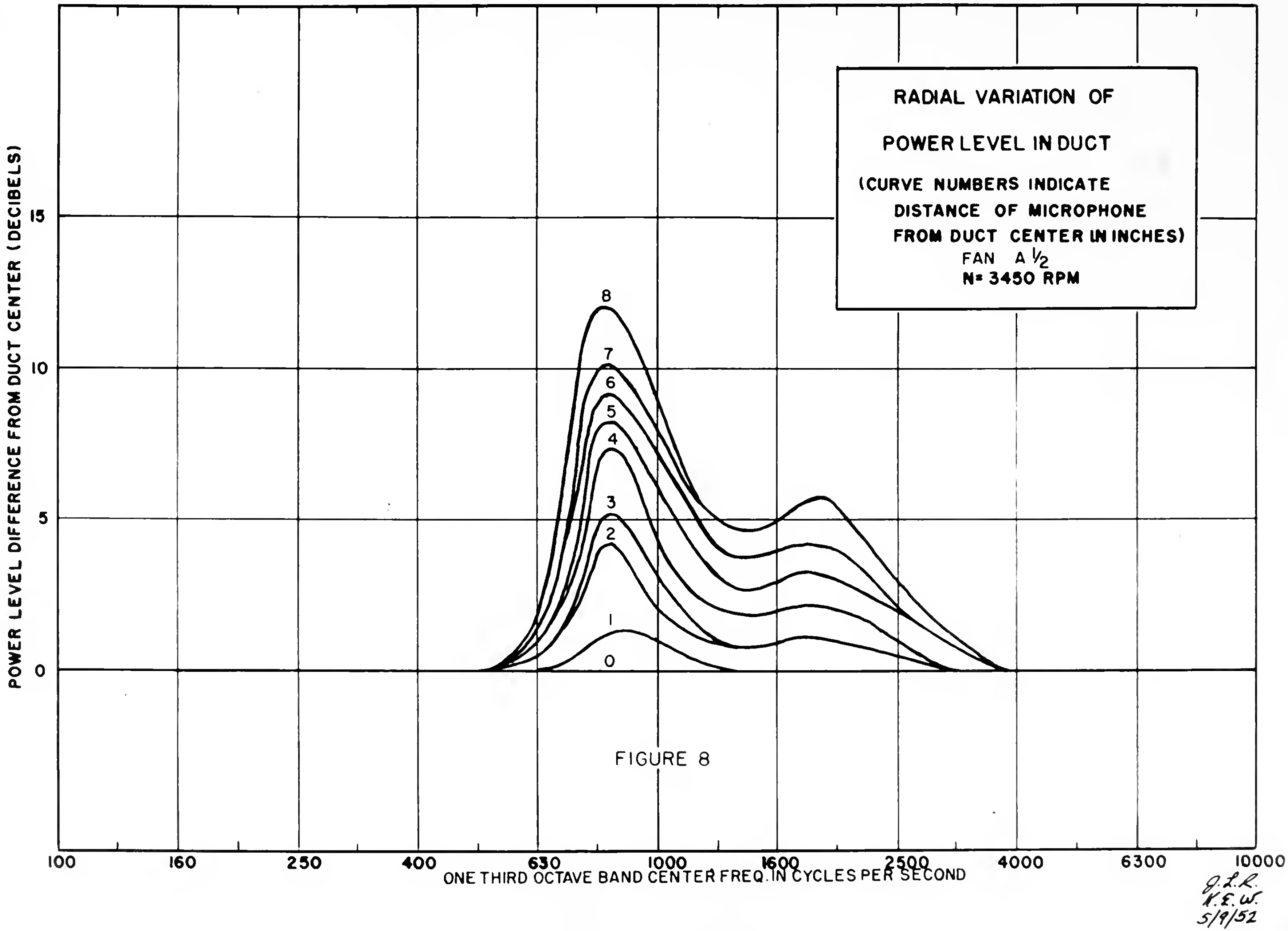
RADIAL VARIATION OF
POWER LEVEL IN DUCT
(CURVE NUMBERS INDICATE
DISTANCE OF MICROPHONE
FROM DUCT CENTER IN INCHES)
FAN A 1/2
N= 3450 RPM
8
7
6
5
4
3
2
1
0
15
10
5
0
POWER LEVEL DIFFERENCE FROM DUCT CENTER (DECIBELS)
100
160
250
400
630
1000
1600
2500
4000
6300
10000
ONE THIRD OCTAVE BAND CENTER FREQ. IN CYCLES PER SECOND
J.L.R.
K.E.W.
5/9/52

FIGURE 8

4. Effect of Windscreen on Microphone

$A\frac{1}{2}$, n = 3450 RPM

			SPL	
f	Band	Ambient	No Screen	With Screen
100	4	57	78	77
125	5	52	76	76
160	6	57	76	75
200	7	51	75	73
250	8	48	77	76
320	9	50	78	78
400	10	50	83	83
500	11	42	79	79
630	12	40	78	77
800	13	46	77	75
1000	14	41	74	73
1250	15	38	77	76
1600	16	40	78	76
2000	17	37	76	73
2500	18	37	75	72
3200	19	33	76	71
4000	20	26	74	70
5000	21	19	69	67
6300	22	19	67	66
8000	23	19	66	63
10000	24	19	63	60

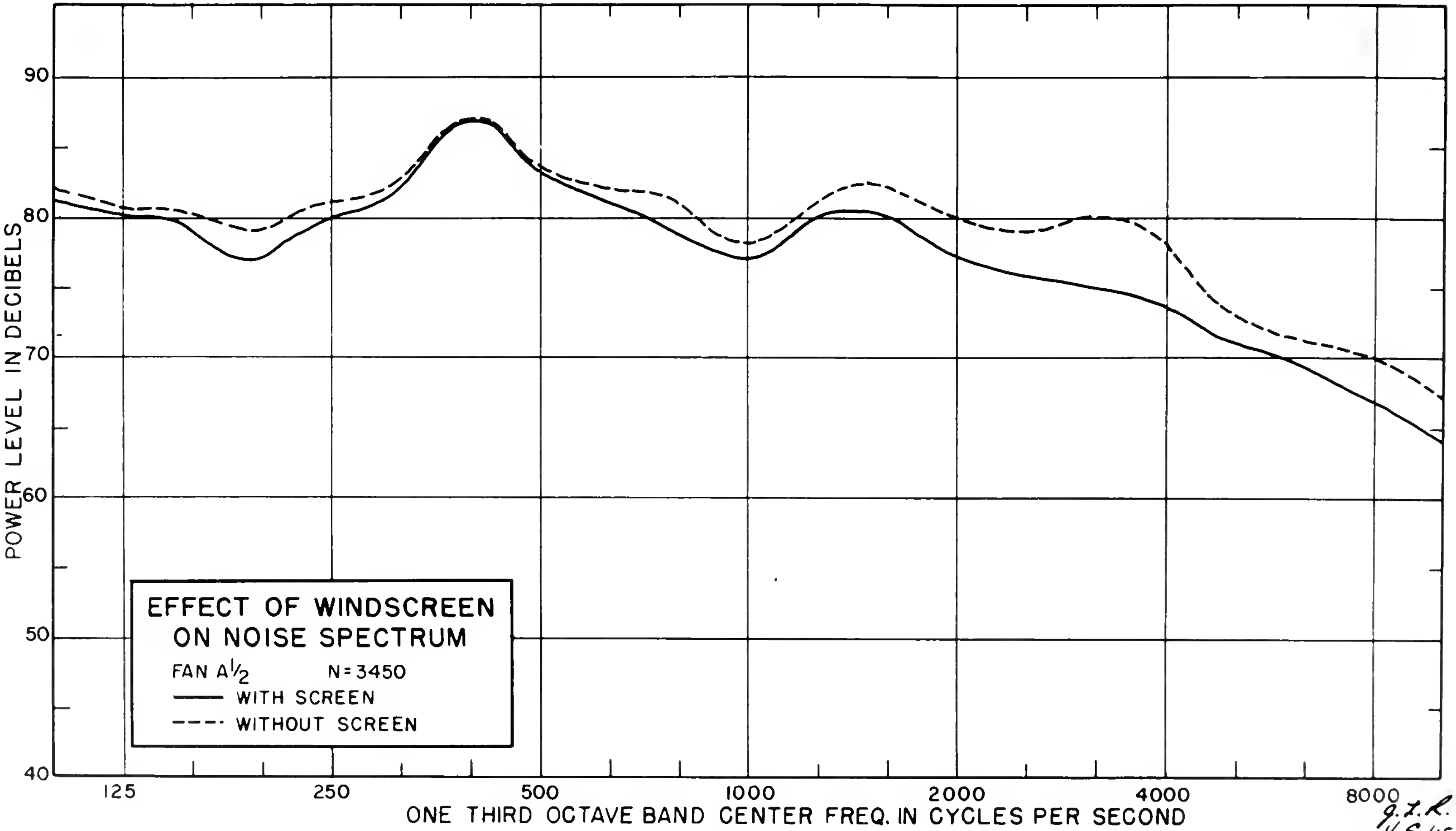

FIGURE 9

G.T.R.
K.E.W.
5/8/52

5. $A\frac{1}{2}$ Fan Test (No Back Pressure)

Band Center Freq.	Band No.	Spectrum Level Corr.	Ambient	n = 800 SPL	n = 800 Spec Level	900 SPL	900 Spec Level	1000 SPL	1000 Spec Level
100	4	12.5	57	65	51.5	68	55.5	66	53.5
125	5	15	52	66	51	64	49	63	48
160	6	16	57	63	46	73	57	69	53
200	7	16.5	51	58	40.5	61	44.5	64	47.5
250	8	17.5	48	60	42.5	62	44.5	63	45.5
320	9	18.5	50	73	54.5	72	53.5	63	44.5
400	10	19.5	50	71	51.5	83	63.5	77	57.5
500	11	21	42	58	37	69	48	71	50
630	12	22	40	52	30	57	35	54	32
800	13	23	46	52	28	57	34	58	35
1000	14	24	41	54	30	56	32	52	28
1250	15	25	38	48	23	57	32	49	24
1600	16	26	40	48	21	56	30	50	24
2000	17	27	37	41	12	45	17	42	13
2500	18	28	37	40	9	40	9	41	11
3200	19	29	33	37	6	39	9	40	10
4000	20	30	26	36	6	38	8	40	10
5000	21	30.5	19	38	7.5	39	8.5	40	9.5
6300	22	31	19	39	8	40	9	41	10
8000	23	31.5	19	34	2.5	36	4.5	37	5.5
10000	24	32	19	28	- 4	31	- 1	31	- 1

		n = 800	900	1000
Overall SPL	0" (On Duct ℄)	82	79	81
	3"	80	89	88
	6"	81	88	93
	8"	82.5	91	95
Average Overall SPL		81.8	87.7	90.8

$A\frac{1}{2}$ Fan Test (No Back Pressure)

Band Center Freq	n = 1100 SPL	Spec Level	1200 SPL	Spec Level	1300 SPL	Spec Level	1500 SPL	Spec Level
100	66	53.5	65	51.5	70	57.5	68	55.5
125	66	51	66	51	64	49	66	51
160	64	47	68	52	69	53	68	52
200	64	47.5	62	45.5	66	49.5	67	50.5
250	64	46.5	64	46.5	68	50.5	72	54.5
320	64	45.5	67	48.5	67	48.5	69	50.5
400	73	53.5	66	46.5	63	43.5	68	48.5
500	82	61	74	53	74	53	64	43
630	68	46	61	39	77	55	66	44
800	58	35	56	33	59	36	60	37
1000	57	33	64	40	56	32	58	34
1250	53	28	57	32	56	31	58	33
1600	52	26	59	33	58	32	60	34
2000	45	17	49	22	49	22	53	26
2500	42	12	46	18	44	16	50	22
3200	42	13	43	14	43	14	46	17
4000	41	11	42	12	43	13	45	15
5000	44	13.5	43	12.5	44	13.5	47	16.5
6300	42	11	44	13	44	13	46	15
8000	40	8.5	42	11.5	41	9.5	43	11.5
10000	36	4	37	5	38	6	40	8

Overall		n = 1100	1200	1300	1500
SPL	0"	85	79	81	82
	3"	92	82	81	84
	6"	97	89	84	89
	8"	98	92	85	90
Average Overall	SPL	92.0	87.0	83.0	86.8

$A\frac{1}{2}$ Fan Test (No Back Pressure)

Band Center Freq	n = 1700 SPL	Spec Level	2000 SPL	Spec Level	2300 SPL	Spec Level	2600 SPL	Spec Level
100	81	68.5	75	62.5	71	58.5	79	66.5
125	68	53	71	56	70	55	73	58
160	68	52	68	52	71	55	71	55
200	70	53.5	68	51.5	70	53.5	69	52.5
250	71	53.5	76	58.5	79	61.5	74	56.5
320	75	56.5	75	56.5	77	58.5	81	62.5
400	70	50.5	72	52.5	74	54.5	74	54.5
500	64	43	69	48	75	54	76	55
630	64	42	66	44	69	47	73	51
800	67	44	74	51	68	45	69	46
1000	59	35	71	47	71	47	73	49
1250	60	35	64	39	66	41	72	47
1600	62	36	65	39	68	42	71	45
2000	56	29	60	33	64	37	66	39
2500	51	23	58	30	62	34	66	38
3200	49	20	54	25	59	30	63	34
4000	47	17	51	21	56	26	61	31
5000	46	15.5	51	20.5	53	22.5	58	27.5
6300	48	17	52	21	54	23	58	27
8000	46	14.5	49	17.5	50	18.5	60	28.5
10000	42	10	46	14	47	15	58	26
Overall SPL 0"	86		86		87		90	
3"	86		86		88		91	
6"	88		86		89		92	
8"	88		87		89		92	
Average Ov. SPL	87.0		86.2		88.3		91.3	

$A\frac{1}{2}$ Fan Test (No Back Pressure)

Band Center Freq	n = 3000 SPL	Spec Level	3200 SPL	Spec Level	3450 SPL	Spec Level
100	79	66.5	79	66.5	78	65.5
125	73	58	78	63	77	62
160	74	58	74	58	75	59
200	72	55.5	73	56.5	74	57.5
250	75	57.5	76	58.5	77	59.5
320	78	59.5	79	60.5	78	59.5
400	80	60.5	83	63.5	83	63.5
500	78	57	78	57	79	58
630	77	55	77	55	78	56
800	73	50	76	53	75	52
1000	74	50	73	49	73	49
1250	75	50	76	52	76	51
1600	73	47	75	49	78	52
2000	70	43	72	45	73	46
2500	71	43	70	42	72	44
3200	68	39	70	41	72	43
4000	66	36	68	38	70	40
5000	62	31.5	65	34.5	66	35.5
6300	62	31	66	35	66	35
8000	64	32.5	65	33.5	63	31.5
10000	62	30	62	30	60	28

Overall	n = 3000	3200	3450
SPL 0"	92	92	93.5
3"	93	93	95
6"	94	94	95
8"	95	95	96
Average OV. SPL	93.6	93.6	95.0

6. $A\frac{1}{2}$ Fan Test (With Back Pressure)

Band Center Freq	n = 1000 SPL	Spec Level	1500 SPL	Spec Level	2000 SPL	Spec Level
100	65	52.5	68	55.5	73	60.5
125	63	48	64	49	70	55
160	70	54	66	50	67	51
200	67	50.5	67	50.5	67	50.5
250	62	44.5	74	46.5	76	58.5
320	62	43.5	68	49.5	75	56.5
400	73	53.5	67	47.5	73	53.5
500	69	48	62	41	67	46
630	54	32	65	43	65	43
800	67	44	59	36	76	53
1000	64	40	58	34	73	49
1250	54	29	58	33	63	38
1600	53	27	60	34	64	38
2000	49	22	54	27	60	33
2500	46	18	52	24	58	30
3200	44	15	50	21	54	25
4000	40	10	49	19	52	22
5000	39	8.5	48	17.5	52	21.5
6300	43	12	50	19	53	22
8000	40	8.5	47	15.5	54	22.5
10000	32	0	44	12	54	22
Overall SPL 0"	81		82		85	
3"	87.5		83		85	
6"	93.5		85		86	
8"	94		87		86	
Average OV. SPL	90.4		85.0		85.5	
Back Pressure inches of H_2O	.06		.10		.16	

$A\frac{1}{2}$ Fan Test (With Back Pressure

Band Center Freq	n = 2500 SPL	n = 2500 Spec Level	3000 SPL	3000 Spec Level	3450 SPL	3450 Spec Level
100	74	61.5	75	62.5	75	62.5
125	76	61	71	56	74	59
160	71	55	72	56	73	57
200	69	52.5	69	52.5	72	55.5
250	74	56.5	75	57.5	75	57.5
320	79	60.5	78	59.5	76	57.5
400	73	53.5	83	63.5	81	61.5
500	74	53	79	58	78	57
630	70	48	79	57	78	56
800	68	45	73	50	81	58
1000	79	55	74	50	76	52
1250	72	47	74	49	77	52
1600	69	43	72	46	79	53
2000	66	39	69	42	73	46
2500	64	36	69	41	72	44
3200	62	33	68	39	72	43
4000	58	28	64	34	69	39
5000	54	23.5	60	29.5	64	33.5
6300	57	26	61	30	65	34
8000	58	26.5	62	30.5	63	31.5
10000	57	25	60	28	60	28

Overal	n = 2500	3000	3450
SPL 0"	87.5	91	93.5
3"	88	92	94
6"	89	94	94
8"	89	95	94
Average OV. SPL	88.3	93.2	93.9
Back Pressure Inches of H_2O	.21	.275	.325

Overall SPL Data at Other Speeds

$A\frac{1}{2}$, With Back Pressure - Ambient SPL = 82

	n = 800	900	1100	1200	1300	1800	2200
Overall SPL							
0"	84	85	85	85.5	85	86	87
3"	85	95.5	87	87.5	86	86.5	87.5
6"	86.5	100.5	89	89	90	89.5	88.5
8"	87.5	96.5	90.5	89	92	91.5	90
Overall SPL Corr. for Ambient							
0"	79.5	82	82	83	82	84	85.5
3"	82	95.5	85.5	86	84	84.5	86
6"	84.5	100.5	88	88	89	88.5	87.5
8"	86	96.5	90	88	91.5	91.0	90
Av. OV. SPL	83.3	95.6	86.8	86.5	87.4	87.4	87.4
Back Press. in. of H_2O	.045	.05	.07	.08	.09	.13	.18

7. $A1\frac{1}{2}$ Fan Test, (No Back Pressure)

Band Center Freq	Band No.	Spectrum Level Corr.	Ambient	n = 800 SPL	Spec Level	900 SPL	Spec Level	1000 SPL	Spec Level
100	4	12.5	61	81	69.5	72	59.5	71	58.5
125	5	15	56	70	45	68	53	70	55
160	6	16	56	65	49	65	49	66	51
200	7	16.5	52	63	46.5	65	48.5	65	48.5
250	8	17.5	48	64	46.5	66	48.5	66	48.5
320	9	18.5	49	66	47.5	64	45.5	64	45.5
400	10	19.5	50	59	39.5	60	40.5	62	42.5
500	11	21	43	61	40.0	58	37	61	40
630	12	22	40	53	31	54	32	56	34
800	13	23	46	54	31	56	33	56	33
1000	14	24	42	58	34	59	35	61	37
1250	15	25	40	56	31	59	34	60	35
1600	16	26	41	55	29	58	32	60	34
2000	17	27	40	50	23	53	26	55	28
2500	18	28	42	46	18	47	19	48	20
3200	19	29	37	44	15	48	18	49	20
4000	20	30	34	45	15	46	16	48	18
5000	21	30.5	29	40	9.5	40	9.5	40	9.5
6300	22	31	26	35	4	37	6	36	5
8000	23	31.5	26	33	1.5	35	3.5	36	4.5
10000	24	32	20	32	0	33	1	34	2

Overall SPL	0"		82	82	81
	3"		84	81	82
	6"		84	82	83
	8"		85	83	84
Average Overall SPL		73.0	83.8	82	82.5
Current (amps)			2.4	2.42	2.43
Voltage			14.2	15.1	16.9

$Al\frac{1}{2}$ Fan Test (No Back Pressure)

Band Center Freq	n = 1100 SPL	Spec Level	1200 SPL	Spec Level	1300 SPL	Spec Level	1500 SPL	Spec Level
100	72	59.5	75	62.5	78	65.5	79	66.5
125	73	58	73	58	73	58	72	57
160	68	52	70	54	73	57	75	59
200	66	49.5	67	50.5	67	50.5	69	52.5
250	68	50.5	70	52.5	69	51.5	71	53.5
320	65	46.5	68	49.5	68	49.5	71	52.5
400	65	45.5	65	45.5	65	45.5	66	46.5
500	61	40	62	41	63	42	68	47
630	57	45	59	37	60	38	62	41
800	58	45	59	36	59	36	62	40
1000	63	39	62	38	64	40	65	42
1250	60	35	61	36	62	37	65	40
1600	60	34	62	36	63	37	65	39
2000	58	31	59	32	61	34	64	37
2500	50	22	52	24	53	25	58	30
3200	51	22	53	24	53	24	54	25
4000	49	19	50	20	51	21	53	23
5000	42	11.5	43	12.5	45	14.5	47	16.5
6300	38	7	39	8	40	9	43	12
8000	37	5.5	37	5.5	39	7.5	42	10.5
10000	35	3	34.5	2.5	35	3	37	5

Overall SPL		1100	1200	1300	1500
	0"	84	84	84.5	86
	3"	84.5	84	85	86
	6"	85	83.5	85	86
	8"	85	83.5	86	87
Aver.Ov.SPL		84.7	83.8	85.2	86.2
Current (amps)		2.44	2.55	2.6	2.78
Voltage		18.2	19.5	21.0	24.3

Al$\frac{1}{2}$ Fan Test (No Back Pressure)

Band Center Freq	n = 1700 SPL	Spec Level	2000 SPL	Spec Level	2300 SPL	Spec Level	2500 SPL	Spec Level
100	75	67.5	82	62.5	76	63.5	80	67.5
125	73	58	75	60	75	60	79	64
160	73	57	74	58	75	59	75	59
200	74	57.5	73	56.5	74	57.5	74	57.5
250	72	54.5	74	56.5	79	61.5	82	63.5
320	72	53.5	74	55.5	76	57.5	78	59.5
400	70	50.5	72	52.5	75	55.5	75	55.5
500	68	47	68	47	72	51	74	53
630	65	43	69	47	71	49	71	49
800	64	41	68	45	71	48	72	49
1000	68	34	74	50	74	50	77	53
1250	68	33	73	48	75	50	77	52
1600	65	39	69	43	71	45	73	47
2000	66	39	69	42	71	44	74	47
2500	63	35	68	40	70	42	73	45
3200	58	29	64	35	69	40	73	44
4000	56	26	60	30	67	37	72	42
5000	50	19.5	55	24.5	59	28.5	65	34.5
6300	47	16	52	21	55	24	60	29
8000	45	14.5	50	18.5	54	22.5	58	26.5
10000	40	8	44	12	48	16	53	21

Overall SPL	n = 1700	2000	2300	2500
0"	86.5	92	92.5	93
3"	86.5	92	93	92.5
6"	86.5	91.5	93	93
8"	87	91.5	93	93
Average Overall SPL	86.6	91.8	92.9	92.9
Current (amps)	2.9	3.05	3.4	3.55
Voltage	27.9	33.3	39.9	45.9

Al$\frac{1}{2}$ Fan Test (No Back Pressure)

Band Center Freq	n = 2600 SPL	Spec Level	3000 SPL	Spec Level	3200 SPL	Spec Level	3450 SPL	Spec Level
100	78	65.5	85	72.5	98	85.5	87	74.5
125	77	62	83	68	87	72	80	65
160	77	61	77	61	80	64	79	63
200	76	59.5	76	59.5	78	61.5	78	61.5
250	80	62.5	78	60.5	79	61.5	80	62.5
320	78	59.5	79	60.5	80	61.5	81	62.5
400	75	55.5	77	57.5	79	59.5	83	63.5
500	74	53	76	55	78	57	82	61
630	71	49	74	52	77	55	79	57
800	72	49	74	51	76	53	78	55
1000	76	52	79	55	81	57	84	60
1250	77	52	79	54	80	55	82	57
1600	73	47	78	52	78	52	79	53
2000	72	45	76	49	77	50	78	51
2500	70	42	73	45	74	46	76	48
3200	70	41	72	43	73	44	74	45
4000	70	40	75	45	76	46	77	47
5000	63	32.5	70	39.5	73	42.5	76	45.5
6300	59	28	63	32	66	35	70	39
8000	56	24.5	61	29.5	63	31.5	65	33.5
10000	52	20	56	24	58	26	61	29

Overall SPL	n = 2600	3000	3200	3450
0"	92.5	94	102	97
3"	92.5	94	102	97
6"	92.5	95	102	96
8"	93	96	102	96
Average Overall SPL	92.6	94.8	102	96.5
Current (amps)	3.76	4.04	4.25	4.6
Voltage	48.8	55	60	70

A1$\frac{1}{2}$ Fan Test (No Back Pressure)

Band Center Freq	n = 3800 SPL	Spec Level	4200 SPL	Spec Level	4600 SPL	Spec Level
100	84	71.5	81	68.5	81	68.5
125	82	67	83	68	83	68
160	80	64	80	64	81	65
200	78	61.5	79	62.5	80	63.5
250	81	63.5	81	63.5	81	63.5
320	79	60.5	82	63.5	82	63.5
400	81	61.5	83	63.5	82	62.5
500	81	60	82	61	86	65
630	80	58	81	59	83	61
800	80	57	82	59	83	60
1000	83	59	84	60	87	63
1250	83	58	85	60	88	63
1600	81	55	82	56	85	59
2000	80	53	82	55	83	56
2500	78	50	80	52	81	53
3200	75	46	78	49	79	50
4000	78	48	79	49	80	50
5000	78	47.5	79	48.5	80	49.5
6300	74	43	77	46	79	48
8000	69	37.5	73	41.5	76	44.5
10000	63	31	68	36	71	39

Overall SPL		n = 3800	4200	4600
	0"	97.5	99.5	100
	3"	97	99.5	100.5
	6"	97.5	100	101
	8"	97.5	100	101.5
Average Overall SPL		97.4	99.8	100.8
Current (amps)		5.0	5.6	6.1
Voltage		78	90	104

8. **Al$\frac{1}{2}$ Fan Test (With Back Pressure)**

Band Center Freq	Band No.	Spectrum Level Corr.	Ambient	n = 800 SPL	Spec Level	900 SPL	Spec Level	1000 SPL	Spec Level
100	4	12.5	60	76	63.5	75	62.5	75	62.5
125	5	15	55	67	52	68	53	70	55
160	6	16	50	65	49	62	46	63	47
200	7	16.5	47	59	42.5	62	45.5	61	44.5
250	8	17.5	44	60	42.5	62	44.5	64	46.5
320	9	18.5	41	59	40.5	60	41.5	61	42.5
400	10	19.5	50	55	35.5	57	37.5	59	39.5
500	11	21	40	59	38	59	38.0	59	38
630	12	22	35	51	29	55	33	55	33
800	13	23	40	51	28	52	29	55	32
1000	14	24	37	55	31	57	33	60	36
1250	15	25	33	53	28	55	30	58	33
1600	16	26	33	56	30	55	29	56	30
2000	17	27	30	48	21	51	24	52	25
2500	18	28	29	42	14	43	15	45	17
3200	19	29	35	43	14	45	16	47	18
4000	20	30	32	43.5	13.5	45	15	47	17
5000	21	30.5	28	38	7.5	39	8.5	40	9.5
6300	22	31	20	31	0	32.5	1.5	33	2
8000	23	31.5	20	32	0.5	33.5	2	35	3.5
10000	24	32	19	31	-1	33	1	34	2
Overall SPL		0"		81		81		82	
		3"		80.5		82		82	
		6"		81		82		82	
		8"		81		82		81	
Average Overall SPL				80.9		81.8		81.8	
Current (amps)				2.54		2.59		2.62	
Voltage				15		16.5		17.8	
Back Pressure				.09		.10		.12	

Al$\frac{1}{2}$ Fan Test (With Back Pressure)

Band Center Freq.	n = 1100 SPL	Spec Level	1200 SPL	Spec Level	1300 SPL	Spec Level	1500 SPL	Spec Level
100	78	65.5	77	64.5	85	72.5	78	65.5
125	74	59	73	58	73	62	72	57
160	65	49	70	54	74	58	71	55
200	62	45.5	63	46.5	65	48.5	67	50.5
250	66	48.5	65	47.5	66	48.5	68	50.5
320	63	44.5	64	45.5	67	48.5	70	51.5
400	60	40.5	62	42.5	62	42.5	66	46.5
500	59	38	60	39	65	44	67	46
630	56	34	58	36	60	38	62	40
800	56	33	57	34	59	36	62	39
1000	61	37	61	37	63	39	65	41
1250	61	36	62	37	63	38	65	40
1600	60	34	64	38	64	38	64	36
2000	54	27	56	29	58	31	62	35
2500	47	19	50	22	51	23	55	27
3200	48.5	19.5	51	22	51	22	55	26
4000	48	18	51	21	51	21	54	24
5000	41	11.5	43	12.5	44	13.5	48	17.5
6300	35	4	37	6	38	7	42	11
8000	36	4.5	37	5.5	37.5	6	41.5	10
10000	36	4	37	5	36.5	3.5	39	7

Overall SPL		1100	1200	1300	1500
	0"	82	88	90	85
	3"	83	87	90	85
	6"	83	86.5	91	85.5
	8"	82	87	90	85.5
Average Overall SPL		82.5	87.2	90.2	85.3
Current (amps)		2.71	2.79	2.85	3.0
Voltage		19.7	21.4	22.6	26.1
Back Pressure		.135	.15	.165	.195

A1$\frac{1}{2}$ Fan Test (With Back Pressure)

Band Center Freq	n = 1700 SPL	Spec Level	2000 SPL	Spec Level	2300 SPL	Spec Level	2500 SPL	Spec Level
100	74	61.5	81	68.5	77	64.5	79	66.5
125	73	58	75	60	75	60	77	62
160	72	56	73	57	74	58	75	59
200	70	53.5	75	58.5	74	57.5	75	58.5
250	70	52.5	73	55.5	76	58.5	80	62.5
320	69	50.5	71	52.5	73	54.5	76	57.5
400	68	48.5	69	49.5	71	51.5	72	52.5
500	69	46	68	47	71	50	72	51
630	65	43	68	46	70	48	71	49
800	63	40	67	44	70	47	71	48
1000	67	43	73	49	74	50	77	53
1250	67	42	72	47	74	49	76	51
1600	66	40	69	43	71	45	72	46
2000	65	38	69	42	70	43	72	45
2500	58	30	65	37	69	41	70	42
3200	57	28	61	32	65	36	67	38
4000	57	27	60	30	64	34	66	36
5000	50	19.5	55	24.5	58	27.5	61	30.5
6300	45	14	50	19	54	23	56	25
8000	43	12.5	47	15.5	52	20.5	54	22.5
10000	40	8	43	11	47	15	50	18

		1700	2000	2300	2500
Overall SPL	0"	85	94	92	92
	3"	86	93.5	93	92
	6"	87.5	94	93	93
	8"	88	94	93	93
Average Overal SPL		86.8	93.9	92.8	92.5
Current (amps)		3.21	3.55	3.8	4.1
Voltage		30.2	36.8	43.8	49.9
Back Pressure		.23	.27	.325	.36

A1½ Fan Test (With Back Pressure)

Band Center Freq	n = 2600 SPL	Spec Level	3000 SPL	Spec Level	3200 SPL	Spec Level	3450 SPL	Spec Level
100	77	64.5	88	75.5	99	86.5	85	72.5
125	78	63	82	67	84	69	79	64
160	75	59	77	61	79	63	78	62
200	74	57.5	76	59.5	77	60.5	76	59.5
250	85	67.5	78	60.5	79	61.5	81	63.5
320	80	61.5	79	60.5	82	63.5	81	62.5
400	74	54.5	76	56.5	79	59.5	86	66.5
500	73	52	74	53	76	55	79	58
630	71	49	74	52	75	53	77	55
800	72	49	74	51	76	53	79	56
1000	76	52	79	55	80	56	82	58
1250	76	51	80	55	80	55	82	57
1600	73	47	78	52	78	52	79	53
2000	72	45	76	49	77	50	79	52
2500	71	43	73	45	74	46	76	48
3200	68	39	71	42	73	44	74	45
4000	67	37	72	42	74	44	75	45
5000	62	31.5	67.5	37	70	39.5	73	42.5
6300	58	27	62	31	65	34	68	37
8000	55	23.5	60	28.5	62	30.5	64	32.5
10000	51	19	55	23	57	25	60	28

Overall SPL	2600	3000	3200	3450
0"	92	97	104	96
3"	92	97	103	96
6"	92	97	103	95.5
8"	93	96	103	96.5
Average Overall SPL	92.4	96.8	103.2	96.0
Current (amps)	4.2	4.65	4.93	5.3
Voltage	50.0	60.0	65.5	73.0
Back Pressure	.38	.45	.49	.54

Al$\frac{1}{2}$ Fan Test (With Back Pressure)

Band Center Freq.	n = 3800 SPL	3800 Spec Level	4200 SPL	4200 Spec Level	4400 SPL	4400 Spec Level
100	88	75.5	80	67.5		
125	87	72	82	67		
160	79	63	79	63		
200	80	63.5	78	61.5		
250	81	63.5	82	64.5		
320	80	61.5	81	62.5		
400	84	64.5	84	64.5		
500	79	58	83	62		
630	78	56	80	58		
800	80	57	83	60		
1000	83	59	84	60		
1250	84	59	86	61		
1600	81	55	82	56		
2000	80	53	82	55		
2500	78	50	80	52		
3200	75	46	77	48		
4000	77	47	78	48		
5000	76	45.5	78	47.5		
6300	72	41	75	44		
8000	68	36.5	71	39.5		
10000	63	31	65.5	33.5		

	n = 3800	4200	4400
Overall SPL 0"	97	99	99.5
3"	98	99	99.5
6"	98	100	100
8"	99	100.5	100
Average Overall SPL	98.0	99.6	99.8
Current (amps)	5.82	6.38	6.65
Voltage	84.5	95.0	102.0
Back Pressure	.61	.66	.7

9. Effect of Reversing Fan Direction $A\frac{1}{2}$, n = 3450 RPM

Octave-Band Analysis

Band Freq Range	Spec Level Corr	Amb	Forward Direction SPL	Forward Direction SPL Corr. for Amb	Forward Direction Spec Level	Back Direction SPL	Back Direction SPL Corr for Amb	Back Direction Spec Level
75 - 150	18.8	55	63	62.5	43.7	62	61	42.2
150 - 300	21.8	55	61.5	61	39.2	60	58.5	36.7
300 - 600	24.8	41	66	66	41.2	65	65	40.2
600 - 1200	27.8	38	60	60	32.2	61.5	61.5	33.7
1200 - 2400	30.8	34	62.5	62.5	31.7	66.5	66.5	35.7
2400 - 4800	33.8	22	59.5	59.5	25.7	58.5	58.5	24.7
4800 - 10 kc	37.2	20	54	54	16.8	52	52	14.8
Overall SPL	0"	82	94			95		
	3"	82	94			95		
	6"	82	95			95		
	8"	82	95			96		
Average Overall SPL		82	94.5			95.2		

C. CALCULATIONS

1. Adapter Design

Circular to Square Cross-Section (Equal Areas)

$\frac{\pi D^2}{4} = S^2$ D = 21.1875" S = 18.76"

D = Diameter in inches

S = Side of Square Section in inches

2. Design of Exponential Horn

$A = A_o e^{mx}$

x = Longitudinal Distance from throat

$\frac{\text{Equiv. Circ. Circum.}}{\lambda} \geq 1$

m = Flaring Constant

$m = \frac{2\pi f_o}{c}$

$\lambda = \frac{c}{f_o}$

f_o = Cutoff Frequency

Lowest fan speed is 1000 RPM

$f_o = \frac{RPM_{fan} \times N}{60}$

7 Blades

N = Fan Blades (7)

$f_o \approx 100$ cps

c = Speed of Sound in Air = 1128 fps

$\lambda = 11.28$ ft.

A_o = Throat Area

A = Area at Station x

Equivalent Circular Circumference (C) = 11.28 Ft. = 125.36 In.

$A_{mouth} = \frac{(C^2)}{4\pi} = 1451.0 \text{ In}^2$ for Square Cross-Section

$S_{mouth} = 38.1$ In.

$mc = 2\pi f_o$

$A_o = 356.0 \text{ In}^2$

$m = \frac{2\pi \times 100}{1128} = 0.557$

$S_o = 18.76$ In.

$\frac{1451.0}{356.0} = e^{0.557 X} = 4.07$ X = 2.52 Ft. (Length of Horn)

2. Design of Exponential Horn (continued)

$A = A_o e^{mx}$ $\qquad A_o = 356.0 \text{ in}^2$

$m = .557$

x(ft)	A_o	e^{mx}	A_x	S_x(in)	
0	356	1	356	18.76	(throat)
0.5	356	1.322	471	21.72	
1	356	1.746	621	24.94	
1.5	356	2.310	822	28.65	
2	356	3.05	1087	32.98	
2.52	356	4.07	1451	38.10	(mouth)

3. Horn Check

$$I = \frac{\bar{p}^2}{\rho c}$$

c = Speed Sound in air, cm/sec

ρ = Density of air, dynes/cm^3

$\bar{p}$ = RMS Pressure, dynes/cm^2

$$IL = 10 \log_{10} \frac{I}{10^{-16}}$$

$$SPL = 10 \log_{10} \frac{\bar{p}^2}{(0.0002)^2}$$

$$\Delta IL = IL_x - IL_{throat} = 10 \log_{10} \frac{\bar{p}_x^2}{\bar{p}_{throat}^2}$$

$$\Delta SPL = SPL_x - SPL_{throat} = 10 \log_{10} \frac{\bar{p}_x^2}{\bar{p}_{throat}^2} =$$

$$= \Delta SPL = \Delta IL$$

$$I = \frac{\pi}{A \times 930}$$

π = Sound Power in watts

A = Area in square feet

$$\Delta IL = 10 \log_{10} \frac{\dfrac{\pi}{A_x \times 930}}{\dfrac{\pi}{A_{throat} \times 930}} = 10 \log_{10} \frac{A_{throat}}{A_x}$$

$$\frac{A_{throat}}{A_x} = \frac{1}{e^{mx}} = e^{-mx}$$

x = Axial distance in horn from throat, feet.

$$\Delta IL = 10 \log_{10}(e^{-mx}) = -10\ mx \log_{10} e =$$

$$(-4.36)\ (0.557)\ (x) = \underline{-2.43x = \Delta IL = \Delta SPL}$$

This gives the theoretical variation of change in sound-pressure level from the horn throat with axial horn distance.

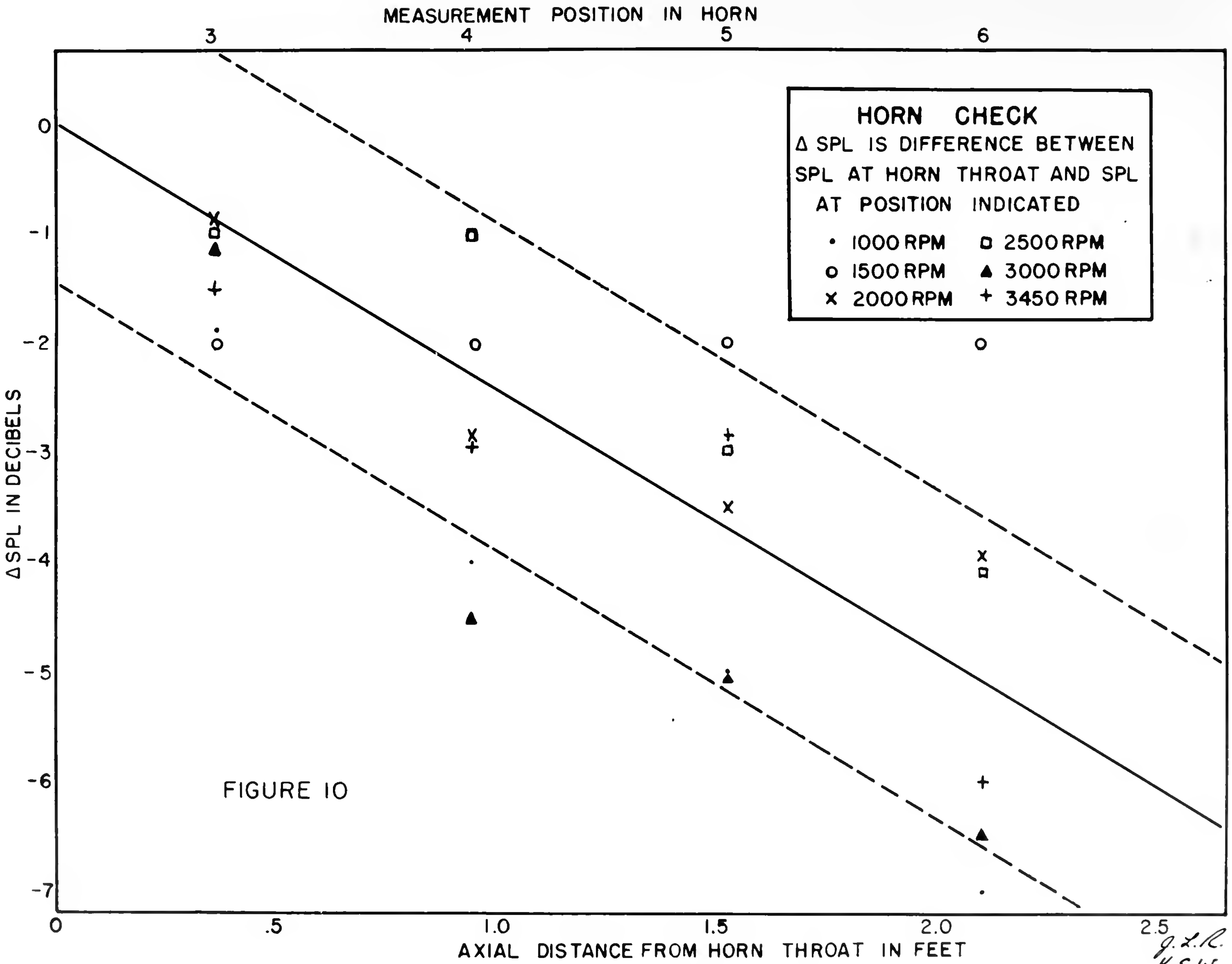

FIGURE 10

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4. Conversion from SPL to PL in the Measuring Duct

SPL = Sound-pressure level in decibels

PL = Power level in decibels

I = Intensity, watts/cm^2

π = Power, watts

A = Duct cross-section area in cm^2

$$SPL = IL = 10 \log_{10} \frac{I}{10^{-16}}$$

$$PL = 10 \log_{10} \frac{\pi}{0.9 \times 10^{-13}}$$

$$\pi = IA$$

$$PL = 10 \log_{10} \frac{IA}{10^{-16}}$$

$$I = 10^{-16} \text{ anti-}\log_{10} \frac{SPL}{10}$$

$$PL = 10 \log_{10} \frac{(10^{-16})(\text{anti-}\log_{10} \frac{SPL}{10})(A)}{0.9 \times 10^{-13}}$$

$$PL = SPL + 10 \log_{10} A - 29.55$$

Duct Diameter = $21\frac{1}{8}''$

$$A = 2.25 \times 10^3 \text{ cm}^2$$

$$PL = SPL + 4.0 \text{ decibels}$$

5. Power Calculations

a. Resistance measurement from blocked rotor test

$I = 0.4$ amps $\qquad$ $V = 0.7$ volts

$$r_2 + r_s = \frac{0.7}{0.4} = 1.75 \text{ ohms} = Ra + s =$$

Resistance of armature plus series field

b. HP calculation - Assume motor windage losses and stray losses = 0

$$HP = \frac{1}{746}\left(IV - I^2 R_{a+s}\right)$$

					$A1\frac{1}{2}$	$A1\frac{1}{2}$	$A\frac{1}{2}$
n	I	V	VI	I^2R_{a+s}	HP calc	$HP \sim n^2$	$HP \sim n^2$
800	2.40	14.2	34	10.10	0.030	---	---
900	2.42	15.1	36.6	10.25	0.035	---	---
1000	2.43	16.9	41.0	10.33	0.041	---	---
1100	2.44	18.2	44.5	10.40	0.046	---	---
1200	2.55	19.5	49.7	11.38	0.051	---	---
1300	2.60	21.0	54.5	11.81	0.057	---	---
1500	2.78	24.3	67.5	13.02	0.073	0.073	0.027
1700	2.90	27.9	80.9	14.70	0.089	0.092	0.033
2000	3.05	33.3	101.5	16.30	0.114	0.128	0.046
2300	3.40	39.9	135.7	20.20	0.155	0.170	0.062
2500	3.55	45.9	162.8	22.00	0.189	0.200	0.073
2600	3.76	48.8	183.4	24.10	0.224	0.216	0.079
3000	4.04	55.0	222.0	28.40	0.259	0.289	0.105
3200	4.25	60.0	255.0	31.60	0.299	0.329	0.120
3450	4.60	70.0	322.0	37.00	0.382	0.382	0.140
3800	5.00	78.0	390.0	43.80	0.465	0.464	---
4200	5.60	90.0	504.0	54.90	0.600	0.566	---
4600	6.10	104.0	635.0	65.10	0.762	0.680	---

$$HP\ A\tfrac{1}{2} = \frac{0.4}{1.1} \times 0.382 = 0.140$$

at rated speed and no back pressure

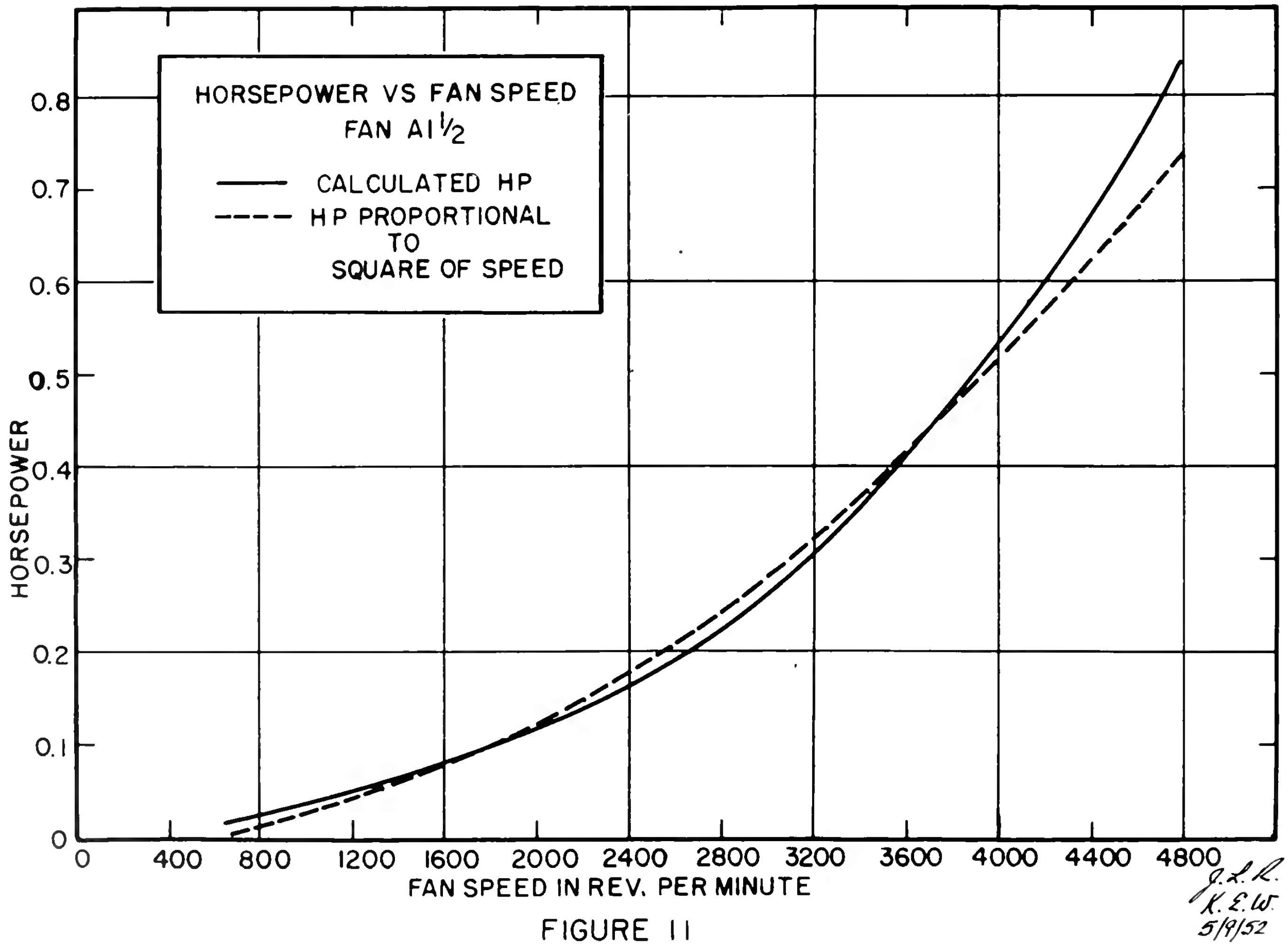
HORSEPOWER VS FAN SPEED
FAN A1½
CALCULATED HP
HP PROPORTIONAL TO SQUARE OF SPEED
HORSEPOWER
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
400
800
1200
1600
2000
2400
2800
3200
3600
4000
4400
4800
FAN SPEED IN REV. PER MINUTE
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FIGURE 11

6. Calculated Curves Based on

$$PL = 121.5 + 3.0 \log_{10} \frac{HP/Blade}{200} - \frac{34800}{n}$$

$A\frac{1}{2}$ (No Back Pressure)

n	HP	$3.0 \log \frac{HP/Blade}{200}$	$\frac{34800}{n}$	PL
2000	.047	-13.4	17.4	91.3
2300	.062	-13.1	15.2	93.7
2600	.080	-12.7	13.4	95.9
3000	.105	-12.4	11.6	98.0
3200	.120	-12.2	10.9	98.9
3450	.140	-12.0	10.1	99.9

$A1\frac{1}{2}$ (No Back Pressure)

2000	.128	-12.1	17.4	92.5
2300	.170	-11.7	15.2	95.1
2600	.216	-11.4	13.4	97.2
3000	.289	-11.1	11.6	99.3
3200	.329	-10.9	10.9	100.2
3450	.382	-10.7	10.1	101.2
3800	.464	-10.4	9.2	102.4
4200	.566	-10.2	8.3	103.5
4600	.621	- 9.9	7.6	104.5

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